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IN-FLIGHT INVESTIGATION OF THE EFFECTS OF PILOT LOCATION AND CONTROL SYSTEM DESIGN ON AIRPLANE FLYING QUALITIES FOR APPROACH AND LANDING

Norman C. Weingarten and Charles R. Chalk

Calspan Report No. 6645-F-7
NASA Contractor Report No. CR-163115

Prepared For:

NASA Dryden Flight Research Center
Edwards Air Force Base
Edwards, California 93523

December 1981
Air Force Contract No. F33615-79-C-3618

19980731 158

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1. Report No. CR 163115	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
In-Flight Investigation of the Effects of Pilot Location and Control System Design on Airplane Flying Qualities for Approach and Landing

5. Report Date
August 1981

6. Performing Organization Code

7. Author(s)
Norman C. Weingarten and Charles R. Chalk

8. Performing Organization Report No.
Calspan Rep. #6645-F-7

9. Performing Organization Name and Address
Arvin/Calspan Advanced Technology Center
P. O. Box 400
Buffalo, New York 14225

10. Work Unit No.

11. Contract or Grant No.
F33615-79-C-3618

12. Sponsoring Agency Name and Address
NASA/Dryden Flight Research Center
Edwards, California 93523
and Air Force Flight Dynamics Laboratory
Wright-Patterson AFB, Ohio 45433

13. Type of Report and Period Covered
Contractor Report
June 1980-June 1981

14. Sponsoring Agency Code

15. Supplementary Notes
Contract jointly sponsored by NASA/DFRC and USAF/FDL, funded through Air Force contract managed by Jack Barry (USAF/FDL).
Technical Monitors: Don Berry (NASA) and Robert Woodcock (USAF)

16. Abstract
A study of the handling qualities of large airplanes in the approach and landing flight phase was performed. An in-flight simulation experiment utilizing the USAF/Calspan Total In-Flight simulator was performed. A one-million pound statically-unstable delta-wing airplane model was used as a baseline about which variations were made. The primary variables were relative pilot position with respect to center of rotation, command path time delays and phase shifts, augmentation schemes and levels of augmentation. The experiment design, its conduct and analysis of the data are described. Results indicate that the approach and landing task with large airplanes is a low bandwidth task. Low equivalent short period frequencies and relatively long time delays can be tolerated only when the pilot is located a considerable distance forward of the center of rotation. As the pilot position is moved aft towards and then behind the center of rotation, as is the space shuttle, pilot ratings are degraded. A multi-loop analysis of pitch attitude and altitude control gave insight into this pilot position phenomenon. The control problem experienced by the pilots, when seated behind the center of rotation, tended to occur at low altitude when they were using visual cues of rate of sink and altitude. These configurations also lack the initial normal acceleration cue from pitch acceleration that conventional large airplane configurations possess. A direct lift controller improved final flight path control of these shuttle-like configurations.

17. Key Words (Selected by Author(s))
Handling Qualities, Flying Qualities Criteria, Flight Control, Stability and Control, Space Shuttle Orbiter, Approach and Landing

18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	213	

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

FOREWORD

This report was prepared by the Calspan Advanced Technology Center, Buffalo, New York, in partial fulfillment of Contract No. F33615-79-C-3618. The report describes a portion of the results of a flight research program performed, under that contract, in the Total In-Flight Simulator (TIFS). The data presented and analyzed in this report is from evaluations of a delta wing configuration similar in design to the space shuttle orbiter. A more extensive report on the overall experiment was published as Air Force AFWAL-TR-81-3118 and Calspan Report No. 6645-F-5.

The flying qualities experiment reported herein was performed by the Flight Research Department of Calspan under joint sponsorship of the Wright Aeronautical Laboratories (Flight Dynamics Laboratory), Wright-Patterson Air Force Base, Ohio, and the National Aeronautics and Space Administration, Dryden Flight Research Center, Edwards, California. Program monitors were Mr. Robert Woodcock from the Air Force Flight Dynamics Laboratory and Donald Berry from NASA Dryden. Mr. Jack Barry was the Program Manager for the overall TIFS programs from the Air Force Flight Dynamics Laboratory.

This report represents the combined efforts of many members of the Flight Research Department. Mr. Charles Chalk was the Principal Investigator and Norman C. Weingarten was the Project Engineer. Dr. Philip A. Reynolds was the Program Manager for the overall TIFS contract. The contributions of the following individuals are also gratefully acknowledged:

Messrs. Nello Infanti, Michael Parrag, and Charles Berthe — TIFS Safety Pilots.
Messrs. Robert Harper, Jr. and Rogers E. Smith — Evaluation Pilots.
Mr. Thomas Gavin — Electronic Systems Engineer.
Mr. Thomas Franclemont — Electronics Maintenance.
Messrs. Raymond Miller and William Frey — Aircraft Maintenance.
Mrs. Janet Cornell and Mrs. Chris Turpin — Report Preparation.

ABSTRACT

A study of the handling qualities of large airplanes in the approach and landing flight phase was performed. An in-flight simulation experiment utilizing the USAF/Calspan Total In-Flight Simulator was carried out to gather data for the analysis effort. A one-million pound statically-unstable delta-wing airplane model was used as a baseline about which variations were made. The primary variables were relative pilot position with respect to center of rotation, command path time delays and phase shifts, augmentation schemes and levels of augmentation. Both longitudinal and lateral-directional characteristics were investigated. The experiment design, conduct of the experiment, and analysis of the data are described. Results are presented in the form of pilot ratings, pilot comments and various analysis techniques. The results indicate that the approach and landing task with large airplanes is a fairly low bandwidth task. Low equivalent short period frequencies and relatively long time delays can be tolerated only when the pilot is located a considerable distance forward of the center of rotation. As the pilot position is moved aft towards and then behind the center of rotation, pilot ratings are degraded. A multi-loop analysis of pitch attitude and altitude control gave insight into this pilot position phenomenon. Altitude loop bandwidth correlated well with pilot ratings. The control problem experienced by the pilots, when flying the airplane while seated behind the center of rotation, tended to occur at low altitude when they were using visual cues of rate of sink and altitude. These aft pilot position configurations, similar to the space shuttle orbiter, also lack the initial normal acceleration cue from pitch acceleration that conventional large airplane configurations possess. A direct lift controller improved final flight path control of the shuttle-like configurations.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF TABLES

LIST OF SYMBOLS

b	=	wing span, ft
$\bar{c}$	=	mean aerodynamic chord, ft
C_D	=	drag coefficient = $D/\bar{q}S$
C_{D_i}	=	$\partial C_D/\partial i$, $i = \alpha$, δ_e, $\deg^{-1}$
$c.g.$	=	center of gravity
C_L	=	lift coefficient = $L/\bar{q}S$
C_{L_o}	=	lift coefficient at zero angle of attack
C_{L_i}	=	$\partial C_L/\partial i$, $i = \alpha$, δ_e, δ_{DLC}, $\deg^{-1}$
C_{L_j}	=	$\left(\frac{2V}{\bar{c}}\right)\partial C_L/\partial j$, $j = \dot{\alpha}$, q, $\deg^{-1}$
C_ℓ	=	rolling moment coefficient = $L/\bar{q}Sb$
C_{ℓ_i}	=	$\partial C_\ell/\partial i$, $i = \beta$, δ_a, δ_r, $\deg^{-1}$
C_{ℓ_j}	=	$\left(\frac{2V}{b}\right)\partial C_\ell/\partial i$, $j = p$, r, $\deg^{-1}$
C_m	=	pitching moment coefficient = $M/\bar{q}S\bar{c}$
C_{m_o}	=	pitching moment coefficient at zero angle of attack
C_{m_i}	=	$\partial C_m/\partial i$, $i = \alpha$, δ_e, $\deg^{-1}$
C_{m_j}	=	$\left(\frac{2V}{\bar{c}}\right)\partial C_m/\partial j$, $j = \dot{\alpha}$, q, $\deg^{-1}$
C_n	=	yawing moment coefficient = $N/\bar{q}Sb$
C_{n_i}	=	$\partial C_n/\partial i$, $i = \beta$, δ_a, δ_r, $\deg^{-1}$
C_{n_j}	=	$\left(\frac{2V}{b}\right)\partial C_n/\partial j$, $j = p$, r, $\deg^{-1}$
C_y	=	side force coefficient = $Y/\bar{q}S$
C_{y_i}	=	$\partial C_y/\partial i$, $i = \beta$, δ_a, δ_r, $\deg^{-1}$
C_{y_j}	=	$\left(\frac{2V}{b}\right)\partial C_y \partial j$, $j = p$, r, $\deg^{-1}$
D	=	drag, lb
DLC	=	direct lift control
dB	=	decibel units for Bode amplitude = 20 $\log_{10}$ (amplitude)
F_{AW}	=	aileron wheel force, lb
F_{ES}	=	elevator wheel force, positive aft, lb
F_{RP}	=	rudder pedal force, lb

g = gravitational constant = 32.17 ft/sec^2

h = altitude of airplane c.g., ft

h_c = commanded change in airplane altitude at pilot station, ft

h_p = altitude of airplane at pilot station, ft

h_{WH} = altitude of airplane at model wheels, ft

h_ε = $(h_c - h_p)$, error between the commanded altitude and altitude at the pilot station, ft

I_{xx}, I_{yy}, I_{zz} = moments of inertia about X, Y, Z body axes, slug-ft^2

I_{xz} = product of inertia about X, Z body axes, slug-ft^2

K_{p_h} = steady state pilot gain in altitude loop closure, rad/ft

K_{P_θ} = steady state pilot gain in attitude loop closure, lb/rad

K_q = loop gain in pitch rate augmentation system, deg/deg/sec

K_α = angle of attack feedback gain, deg/deg

L = lift, lb

L, M, N = moments about X, Y, Z body axes, ft-lb

m = mass of airplane, slugs

n_y, n_z = lateral, normal acceleration, g's

p, q, r = roll, pitch, yaw rates, deg/sec

$PIOR$ = pilot-induced oscillation rating

PR = pilot rating

$\measuredangle_{PC}$ = phase angle of pilot compensation, $\tan^{-1}(\tau_L \omega_{BW})$, deg

$\bar{q}$ = dynamic pressure = $\frac{1}{2}\rho V^2$, lb/ft^2

s = Laplace operator, sec^{-1}

S = reference wing area, ft2

T = total thrust, lb

T_D = equivalent time delay from equivalent systems analysis, sec

T_q = integration time constant in pitch rate augmentation system, sec

T_1 = notation for level of delay in configuration description

t_1 = effective time delay from maximum slope intercept method, sec

Δt = rise time from time history criteria analysis, sec

V or v = true airspeed, ft/sec

V_I = inertial airspeed, ft/sec

V_x, V_y, V_z = velocity components along X, Y, and Z body axes, ft/sec

W = airplane weight, lb

X, Y, Z = body axes, X-Z plane is in plane of symmetry with X directed forward parallel to the fuselage reference line, Z directed downward, and Y directed out the right wing

X_{MP} = distance along X-body axis between c.g. and pilot station, ft

X_{PCR} = distance along X-body axis between instantaneous center of pitch rotation and pilot station, ft

Y_{c_θ} = aircraft θ/F_{ES} transfer function

Y_{P_h} = pilot describing function in altitude loop closure

Y_{P_θ} = pilot describing function in attitude loop closure

Z_{SP} = vertical distance between pilot station and X-stability axis, negative for pilot above stability axis, ft

α = angle of attack, deg

α_g = turbulence component of angle of attack, deg

α_T = total angle of attack with respect to true airspeed, deg

α_I = inertial angle of attack with respect to inertial velocity,deg

β = sideslip, deg

β_g = turbulence component of sideslip, deg

β_T = total sideslip with respect to true airspeed, deg

β_I = inertial sideslip with respect to inertial velocity, deg

γ = flight path angle, deg

δ_a = aileron surface deflection, positive left T.E. down, deg

δ_{AW} = aileron wheel deflection, positive clockwise, deg

δ_e = elevator surface deflection, positive T.E. down, deg

δ_{EC} = elevator column deflection, positive aft, inch

δ_r = rudder surface deflection, positive T.E. left, deg

δ_{RP} = rudder pedal deflection, positive right pedal forward, inch

δ_{th} = throttle lever position, deg

$[\Delta A/\Delta \measuredangle]_\theta$ = slope of Bode amplitude with phase for the airplane plus pilot delay at reference frequency for pitch attitude loop, dB/deg

$\Delta \measuredangle_\theta$ = differential phase angle of the airplane plus pilot delay at reference frequency for pitch attitude loop, deg

ζ	=	damping ratio
ζ_d	=	damping ratio of Dutch roll mode
ζ_{ph}	=	damping ratio of phugoid mode
ζ_{sp}	=	damping ratio of short period mode
θ	=	pitch attitude, deg or rad
θ_c	=	commanded change in airplane pitch attitude, deg or rad
θ_ε	=	$(\theta_c-\theta)$, error between commanded pitch attitude and airplane pitch attitude, deg or rad
λ	=	aperiodic real root magnitude, sec^{-1}
ρ	=	air density, $slug/ft^3$
σ_i	=	mean square gust intensity, $i = \alpha, \beta$, deg
τ_L	=	time constant of pilot's lead element, sec
τ_{pitch}	=	time constant of pitch command prefilter, sec
τ_{roll}	=	time constant of roll command prefilter, sec
τ_R	=	time constant of roll mode, sec
τ_s	=	time constant of spiral mode, sec
ϕ	=	bank angle, deg
ω_{BW}	=	bandwidth frequency, rad/sec
ω_d	=	undamped natural frequency of Dutch roll mode, rad/sec
ω_{ph}	=	undamped natural frequency of phugoid mode, rad/sec
ω_{sp}	=	undamped natural frequency of short period mode, rad/sec

SUBSCRIPTS

c.g.	-	center of gravity
DLC	-	direct lift control
e	-	equivalent parameter from equivalent system analysis
g	-	turbulence component
I	-	inertial quantity
m	-	model quantity
MGP	-	model gear to pilot
MGR	-	model gear to TIFS radar altimeter

Subscripts, cont'd

MP or PM	-	model quantity at pilot station
MTCG	-	model quantity transformed to TIFS c.g.
P	-	quantity at pilot station
TIFS or unsubscripted	-	TIFS quantity at its c.g.
WH	-	model wheel height

Section 1
INTRODUCTION

The objective of this in-flight research program, utilizing the Air Force Wright Aeronautical Laboratory/Calspan Total In-Flight Simulator (TIFS), was to obtain data applicable to Flight Phase Category C operation of Class III airplanes, i.e., approach and landing task for very large (one million pound), low-load factor airplanes. The overall experiment was to provide data on the following factors:

- Minimum short period dynamics
- The need for absolute n/α limits
- Effect of normal acceleration cues
- Augmentation system bandwidth
- Control system time delay and phase shift limits
- Multi-loop control in landing
- Lateral acceleration tolerable to pilot
- Demonstration of lateral-directional augmentation concept

Only that portion of the data which is most applicable to the space shuttle orbiter design is reported in this document. See Calspan Report No. 6645-F-5 or Air Force Report AFWAL-TR-81-3118 for a more extensive treatment of the overall experiment.

Two Calspan evaluation pilots participated in this program with one pilot evaluating all of the test configurations and the second pilot evaluating approximately one-half of the test configurations.

Pilot comments and ratings were recorded in flight. This data is considered as the principal data obtained from this program. In addition, model responses and data pertinent to trajectory analysis was recorded on board during the performance of the evaluation task.

In the overall experiment, three different basic pilot-aircraft models were generated to evaluate pilot position versus instantaneous center of pitch rotation. The aerodynamics and control systems of all of these configurations were essentially the same except for the value of Z_{δ_e}, or lift due to elevator deflection, which was used to shift the center of rotation. The three basic configurations were:

Long Aft Tail	-	a generic conventionally designed aircraft.
Canard	-	pitching moment controller forward which shifts center of rotation aft, similar to a slender arrow-wing supersonic cruise design with a canard.
Short Aft Tail	-	a generic delta wing design with elevons for pitch and roll control, shifts center of rotation forward of pilot, similar to the space shuttle orbiter design.

Combined with the three basic configurations were two different types of pitch augmentation systems: an angle of attack feedback system and a pitch rate feedback system. Control system gains were varied to augment the basic,statically unstable airframe up to Level 1 handling qualities.

Included in the command paths were different levels of extra transport delays (representative of digital control systems) and first order prefilters (representative of structural filters).

A more detailed description of the Short Aft Tail configurations which were evaluated are outlined and illustrated in Section 2 along with other details of the experiment design. Section 3 presents the mechanization of the experiment including the description of the TIFS setup. Section 4 presents the results of the program, including data collected and analysis. Section 5 contains the conclusions.

Section 2

EXPERIMENT DESIGN

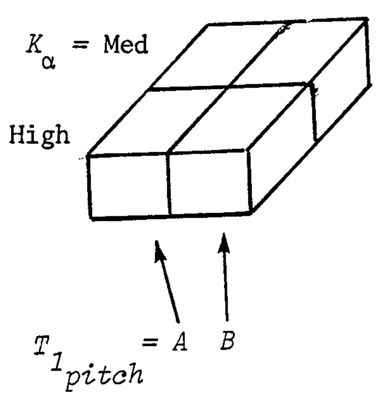
2.1 CONFIGURATION DESCRIPTION

This flight research program consisted of two sets of configurations with detail variations which are outlined and illustrated by the following discussion and diagrams.

The two sets of configurations were intended to explore the interactions of basic configuration factors together with either an angle of attack augmentation or a pitch rate augmentation system similar to the space shuttle design. The α augmentation system is shown in Figure 1. The α signal used was an inertial quantity which eliminated direct turbulence effects on the feedback signal. The α feedback gain was varied, along with the effective time delays in the pilot's command path to the elevator. This configuration set is illustrated by the following diagram.

Set 1 – Short Aft Tail

α-Augmentation



$X_{mp} = 50$ ft

$X_{PCR} = -10$ ft

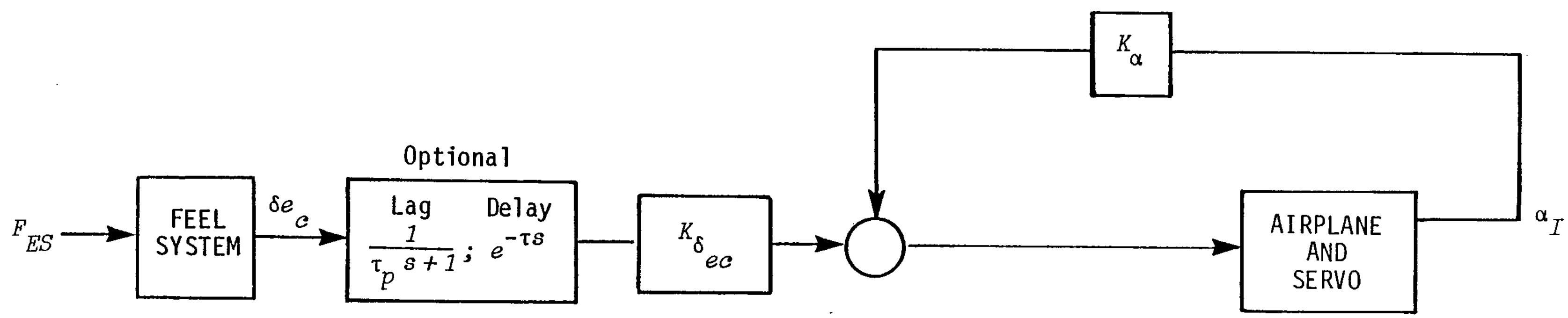


Figure 1. ANGLE OF ATTACK AUGMENTATION

Some of the terms used in these diagrams and in the body of the report are defined below:

$T_{1_{pitch}}$ - notation used to define the effective time delay of the TIFS model following system and the optional elements inserted into the command path. The effective time delay of these portions of the total system is defined by the maximum slope intercept method described in Appendix V-B.

$T_{1_{pitch}} = A$ - nominal effective time delay of the TIFS model following delay in pitch (.06 sec).

$= B$ - "A" delay (.06 sec) plus first order prefilter lag ($\tau_{pitch} = .111$) such that T_1 for these two elements was $T_1 = .13$ sec.

$= C$ - "B" delay plus transport delay (.07 sec) such that T_1 for the three elements was .20 sec.

In the data analysis, the total effective time delay, t_1, is used. See Section 4.2.

The X_{mp} and X_{PCR} refer to the pilot position with respect to the center of gravity and center of rotation, respectively, for each configuration. These are discussed in detail later in this section.

The stability and control derivatives for the basic configuration were kept constant, and equivalent to those of a one-million pound C-5 or Boeing 747. The initial normal acceleration due to a pitch input at the location ℓ_x along the X-body axis can be defined as:

$$n_z(0) = \frac{1}{g}\left[\frac{Z_{\delta_e}}{M_{\delta_e} + Z_{\delta_e} M_{\dot{w}}} - \ell_x\right]\dot{q}(0)$$

where ℓ_x is the point of interest along the X-body axis. At the center of rotation (ℓ_{CR}), $n_z(0) = 0$. Therefore,

$$\ell_{CR} = \frac{Z_{\delta_e}}{M_{\delta_e} + Z_{\delta_e} M_{\dot{w}}}$$

Using the above relation, M_{δ_e} and Z_{δ_e} were selected to obtain a center of rotation similar to the shuttle orbiter. The quadratic drag polar $(C_{D_o} + C_{D_\alpha}\alpha + C_{D_{\alpha}}\alpha^2)$ was chosen to put the aircraft just barely on the back side of the power required curve at 150 KIAS. The dimensional data and stability derivatives are presented in Section 2.2.

The actual pilot location in the fuselage of the airplane is defined in Table 1 and graphically shown in Figure 2. The vertical dimension in the body axes system has been varied in each configuration such that the height of the pilot above the X-stability axis was constant at $Z_{sp} = -18$ ft. This was done to keep the lateral acceleration environment at the model cockpit and the eye height at simulated touchdown constant.

The pitch damping of the base unaugmented airplanes was such that only α feedback was required to augment the airplanes toward Level 1 short period dynamics. The K_α gain was chosen such that the resulting dynamics were:

K_α = Medium $\qquad \omega_{sp}^2 \Big/ \frac{n_z}{\alpha} = .096$ — Level 2 and 3 boundary for $n_z/\alpha = 4.15$ g/rad.

K_α = High $\qquad \omega_{sp}^2 \Big/ \frac{n_z}{\alpha} = .16$ — Level 1 boundary for $n_z/\alpha = 4.15$ g/rad.

Actual control system parameters are presented in Section 2.2. Figure 3 shows where these configurations appear on the MIL-F-8785C short period requirements. Equivalent system analysis was performed on the configurations after the flight program was completed and revised values for the equivalent short period frequencies were obtained. This analysis is presented in Appendix V-A.

Configuration set 2 was a partial repeat of set 1, but with the α augmentation system replaced by pitch rate augmentation plus integral path in the forward loop. See Figure 4 for the control system design. This control system had two extra features. One was an angle of attack limiter which started adding pitch down commands when the angle of attack increased

TABLE 1

PILOT POSITION WITH RESPECT TO MODEL C.G.
AND PITCH CENTER OF ROTATION
(Body axis, ft)

X_{mp} = X distance from model C.G. to pilot

X_{PCR} = X distance from pitch center of rotation to pilot

Configuration	X_{mp}	X_{PCR}
Base Short Aft Tail	50	-10.0
Short Aft (Pilot @ 70')	70	10.0
Short Aft (Pilot @ 110')	110	50.0

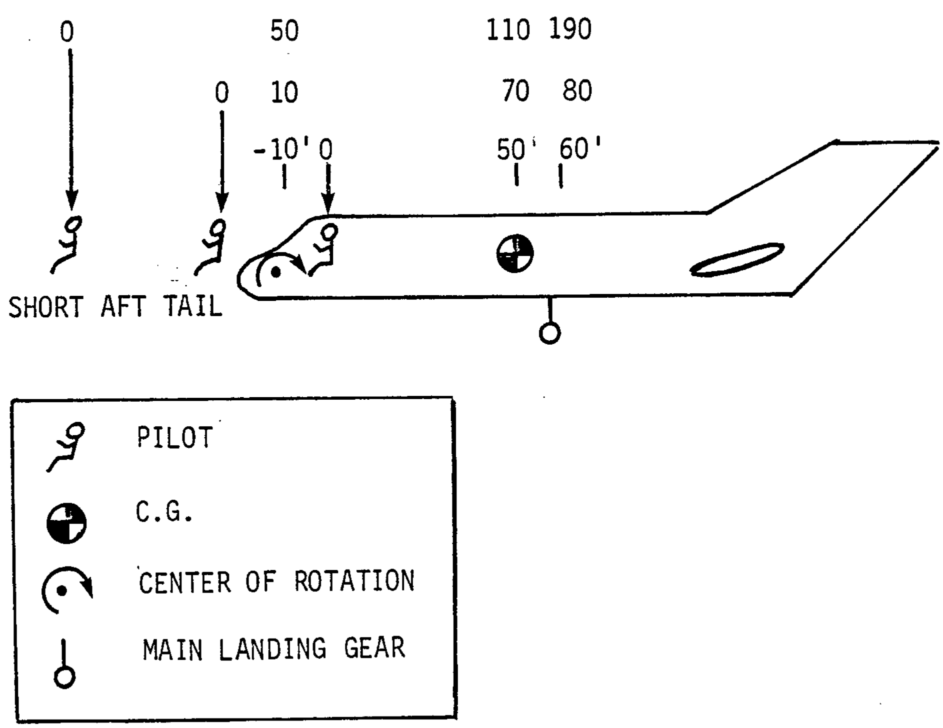


Figure 2. RELATIVE LOCATIONS OF PILOT, C.G., CENTER OF ROTATION, AND MAIN LANDING GEAR OF VARIOUS CONFIGURATIONS

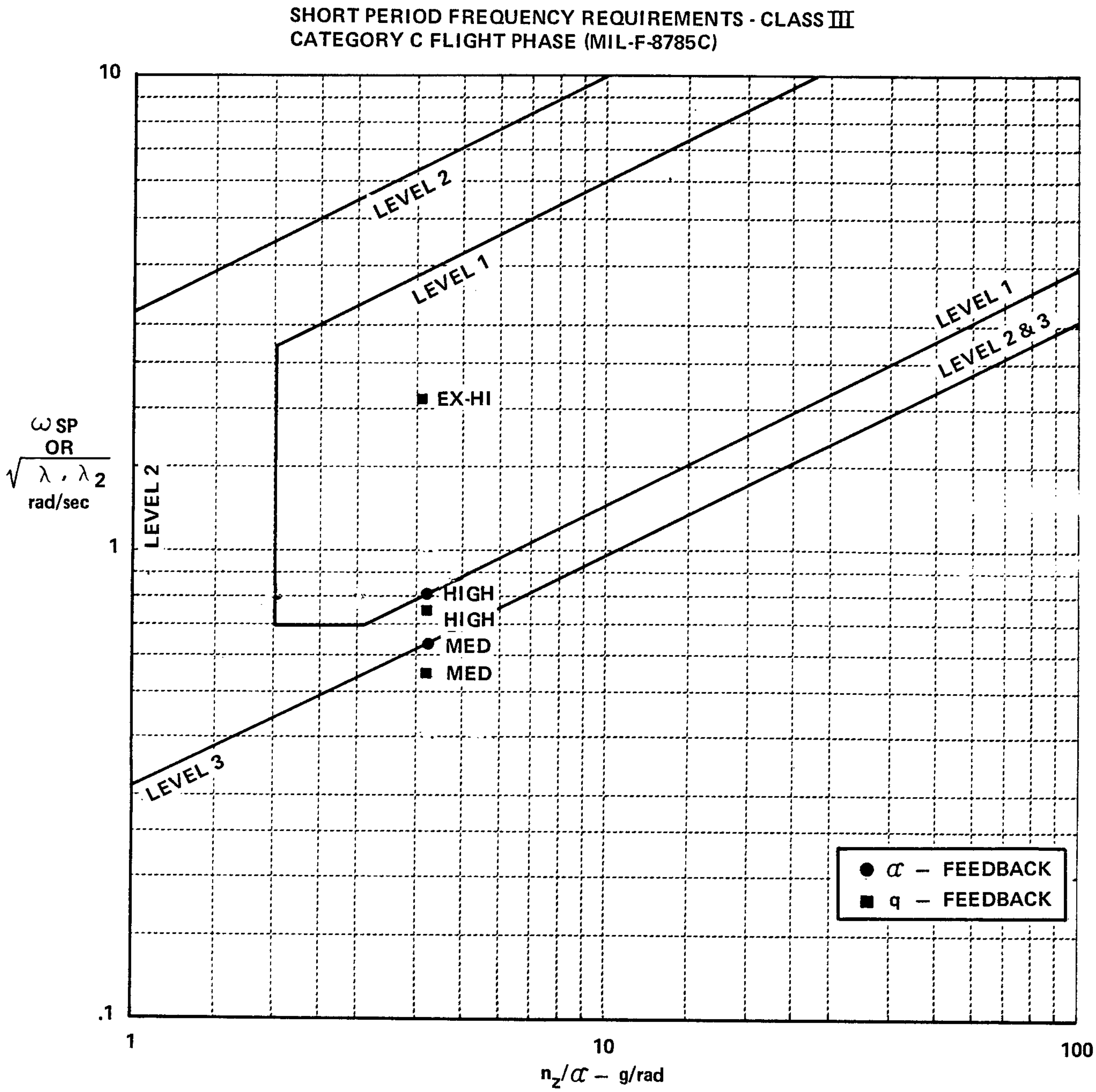
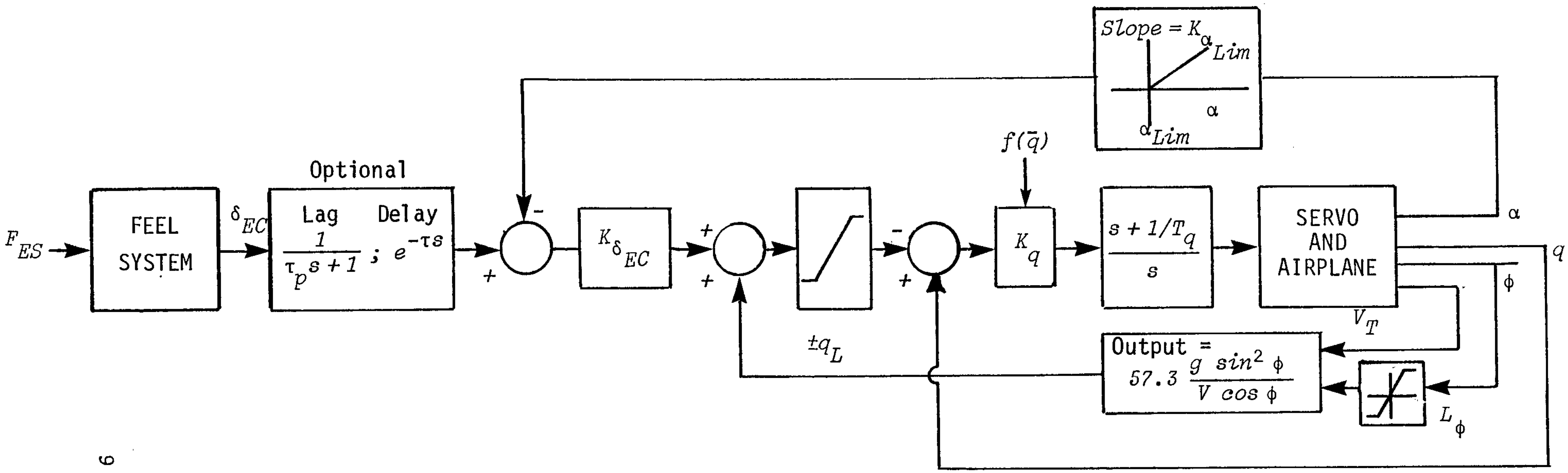


Figure 3. AUGMENTATION LEVELS VS ω_{SP} REQUIREMENTS



$\pm q_L = -\frac{g}{V_T} [\pm n_L + \cos\theta \ \cos\phi]$, n_L set at $1.3g$ just to check operation in tests, not used in evaluations

L_ϕ ∿ Limit bank angle for which elevator is compensated for level turn (± 45 deg)

K_q ∿ Loop gain establishes dynamics, function of $\bar{q}$

$K_{\delta_{e_c}}$ ∿ Command gain, set by pilot

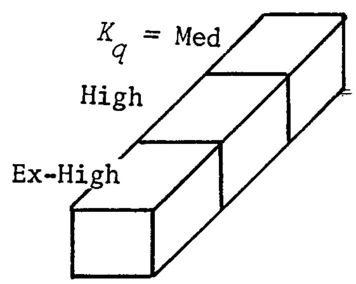
$\frac{1}{T_q}$ ∿ Integral/Proportional Ratio Influence Augmented Dynamics

Figure 4. PITCH RATE AUGMENTATION SYSTEM

beyond a chosen value. The other was a pitch compensator to keep the nose level in a turn without requiring pilot inputs. Since this latter system required a division by cos ϕ which becomes very small at large bank angles, it was limited to bank angles of less than 45 degrees. There was also a limiter on the total pitch rate commanded. This was a function of true speed, pitch attitude and bank angle and was used to limit the maximum load factor (n_L). This limiter was not used in the evaluations but only tested at a load factor of 1.3 g's in the checkout phase of the flight program. All of the extra features in the q augmentation system worked properly and reduced pilot workload in these configurations.

The q augmentation configuration set is illustrated by the following diagram:

Set 2 – Short Aft Tail q Augmentation



$T_{1_{pitch}} = A$

$X_{mp} = 50$ ft.

$X_{PCR} = -10$ ft.

The q augmentation parameters (K_q and T_q) on Figure 4 were selected to give augmented dynamics analogous in an "equivalent system" sense to the short period dynamics of the α augmented configurations of set 1. The K_q gain was inversely proportional to dynamic pressure, $\bar{q}$, to keep the dynamics constant when speed changed. The gain calculations were done before the equivalent system parameters of Appendix V-A were obtained. Specifically, the value for T_q was arbitrarily set at 1 second and the K_q gain varied until the pitch rate time history from a step input reached a maximum at the same time as that for

the equivalent α augmented configuration. Actual control system parameters are presented in Section 2.2. Figure 3 shows where these configurations appear on the MIL-F-8785C short period requirements. Equivalent system analysis of these configurations are presented in Appendix V-A.

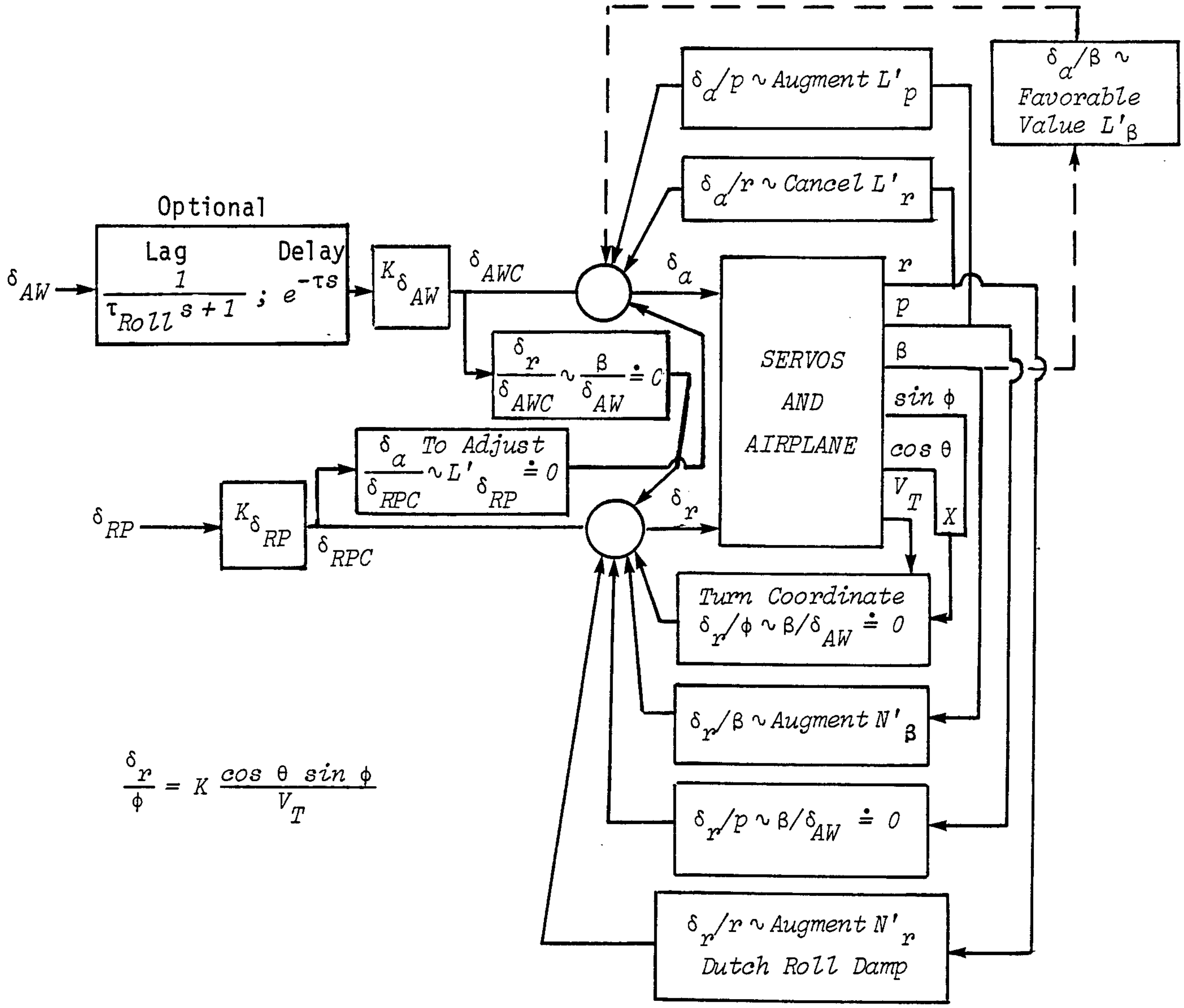
In addition to the above configurations, which were flown at their respective nominal pilot positions, a few extra evaluations were flown with the pilot position shifted. This was done to gather data on the effect of initial normal acceleration and altitude cues on the pilot. These were all run with $T_{1_{pitch}} = A$:

Short Aft Tail, High q, $X_{mp} = 70'$, $X_{PCR} = 10'$
Short Aft Tail, High q, $X_{mp} = 110'$, $X_{PCR} = 50'$

The lateral-directional augmentation was set up such that the airplane rolled and turned in response to roll controller commands without inducing sideslip. The control system design is presented in Figure 5. Actual control system parameters are presented in Section 2.2.

The lateral-directional augmentation system illustrated in Figure 5 was used to achieve good lateral-directional flying qualities for all the configurations. It used $\tau_R = .87$ sec with $T_{1_{roll}} = A$ (nominal effective time delay of the TIFS model-following delay in roll (.12 sec) and set the pilot at $Z_{sp} = -18$ ft.

A configuration set was planned to explore the flying qualities of large space shuttle-type vehicles performing unpowered approaches and landings and to determine how much the pitch flying qualities of such a vehicle would be degraded by time delay in the pitch command channel. Due to the lack of time and funds, this experiment was not carried out. However, the results of the Short Aft Tail model evaluations are applicable to large shuttle configurations due to its similarity in normal acceleration response, i.e., with the pilot near or aft of the pitch center of rotation. In addition, an extra configuration with the approximate shuttle delay (an equivalent time delay of



$$\frac{\delta_r}{\phi} = K\frac{\cos\theta\ \sin\phi}{V_T}$$

Augments primary derivatives, cancels coupling, uses bank angle for turn coordination, feeds back β measured as a psuedo inertial signal.

Figure 5. LATERAL - DIRECTIONAL CONTROL SYSTEM

$T_{1_{pitch}}$ = .35 seconds plus feel system) was evaluated. This is the $T_1 = C$ level plus an extra .11 sec transport delay. The use of a direct lift control device for precise flight path control was also investigated with the Short Aft Tail configuration.

Aerodynamic, control, and feel system representation of each of the Short Aft Tail configurations are presented in the next subsection. Transfer function representations of each of these configurations are presented in Appendix I. Step input time histories for pitch, roll and yaw commands for each of the Short Aft Tail configurations are presented in Appendix II.

2.2 MODEL EQUATIONS OF MOTION, AERODYNAMICS AND CONTROL SYSTEM PARAMETERS

The equations of motion programmed in the TIFS model computer were:

Force Equations (all angular terms in degrees)

$$\dot{V}_I = -\frac{\bar{q}S}{m}(C_D \cos\beta_I - C_y \sin\beta_I) - g\sin\gamma + \frac{T}{m}\cos\alpha_I\cos\beta_I$$

where: $\sin\gamma = \cos\beta_I(\cos\alpha_I \sin\theta - \sin\alpha_I\cos\theta\cos\phi) - \sin\beta_I\cos\theta\sin\phi$

$$\dot{\alpha}_I = -\frac{(57.3)\bar{q}SC_L}{mV_I\cos\beta_I} + \frac{(57.3)g}{V_I\cos\beta_I}[\cos\theta\cos\phi\cos\alpha_I + \sin\theta\sin\alpha_I]$$

$$+ q_I - \tan\beta_I[p_I\cos\alpha_I + r_I\sin\alpha_I]$$

$$-\frac{T\sin\alpha_I(57.3)}{mV_I\cos\beta_I}$$

$$\alpha_I = \sin^{-1}\frac{V_{Z_I}}{V_I\cos\beta_I} = \int\dot{\alpha}_I dt$$

$$\alpha_T = \alpha_I + \alpha_g$$

$$\dot{\beta}_I = \frac{(57.3)\bar{q}S}{mV_I}(C_y\cos\beta_I + C_D\sin\beta_I)$$

$$+ \frac{(57.3)g}{V_I}[\cos\theta\cos\beta_I\sin\phi - \sin\beta_I(\cos\theta\cos\phi\sin\alpha_I$$

$$- \sin\theta\cos\alpha_I)]$$

$$+ p_I\sin\alpha_I - r_I\cos\alpha_I$$

$$-\frac{T\cos\alpha_I\sin\beta(57.3)}{mV_I}$$

$$\beta_I = \sin^{-1}\frac{V_{Y_I}}{V_I} = \int\dot{\beta}_I dt$$

$$\beta_T = \beta_I + \beta_g$$

Moment Equations (Body axes)

$$\dot{q}_I = \frac{(57.3)\bar{q}S\bar{c}}{I_{yy}} [C_m] + \left(\frac{I_{zz} - I_{xx}}{I_{yy}}\right) \frac{p_I r_I}{57.3} + \frac{I_{xz}}{I_{yy}}\left(\frac{r_I^2 - p_I^2}{57.3}\right)$$

$$\dot{p}_I = \frac{(57.3)\bar{q}Sb}{I_{xx}} [C_\ell] + \left(\frac{I_{yy} - I_{zz}}{I_{xx}}\right) \frac{q_I r_I}{57.3} + \frac{I_{xz}}{I_{xx}}\left(\dot{r}_I + \frac{p_I q_I}{57.3}\right)$$

$$\dot{r}_I = \frac{(57.3)\bar{q}Sb}{I_{zz}} [C_n] + \left(\frac{I_{xx} - I_{yy}}{I_{zz}}\right) \frac{q_I p_I}{57.3} + \frac{I_{xz}}{I_{zz}}\left(\dot{p}_I - \frac{q_I r_I}{57.3}\right)$$

The non-dimensional aerodynamic coefficients were defined by the following equations:

$$C_D = C_{D_o} + C_{D_\alpha}\alpha + C_{D_{\alpha^2}}\alpha^2 + C_{D_{\delta_e}}\delta_e + C_{D_{G.E.}} \cdot f_{G.E.}(h)$$

$$C_L = C_{L_o} + C_{L_\alpha}\alpha + C_{L_{\delta_e}}\delta_e + C_{L_{\delta_{DLC}}}\delta_{DLC} +$$

$$\frac{\bar{c}}{2V}(C_{L_q} q + C_{L_{\dot{\alpha}}}\dot{\alpha}) + C_{L_{G.E.}} \cdot f_{G.E.}(h)$$

$$C_y = C_{y_\beta}\beta + C_{y_{\delta_a}}\delta_a + C_{y_{\delta_r}}\delta_r + \frac{b}{2V}(C_{y_p} p + C_{y_r} r)$$

$$C_\ell = C_{\ell_\beta}\beta + C_{\ell_{\delta_a}}\delta_a + C_{\ell_{\delta_r}}\delta_r + \frac{b}{2V}(C_{\ell_p}p + C_{\ell_r}r)$$

$$C_m = C_{m_o} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e + \frac{\bar{c}}{2V}(C_{m_q}q + C_{m_{\dot\alpha}}\dot\alpha)$$

$$+ C_{m_{G.E.}} \cdot f_{G.E.}(h)$$

$$C_n = C_{n_\beta}\beta + C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r + \frac{b}{2V}(C_{n_p}p + C_{n_r}r)$$

The constant physical characteristics for all of the configurations are listed below:

Constant Large Aircraft Characteristics

Weight (W)	= 1,000,000 lb
Mass (m)	= 31,085. slugs
Wing area (S)	= 9,060 ft^2
Span (b)	= 258 ft
Chord ($\bar{c}$)	= 35.7 ft
I_{xx}	= 55,000,000 slug-ft^2
I_{yy}	= 78,000,000 slug-ft^2
I_{zz}	= 127,000,000 slug-ft^2
I_{xz}	= 0 slug-ft^2

All configurations trimmed at:

V_{IAS}	= 150 knots
V_{true}	= 253.2 ft/sec, sea level
$\bar{q}$	= $1/2\ \rho V_t^2$ = 76.29 lb/ft
$C_{L_{trim}}$	= 1.45
$C_{D_{trim}}$	= .16
$Thrust_{trim}$	= 110,590 lb
α_{trim}	= 4 degrees
$\delta_{e_{trim}}$	= 0

Elevator, aileron, rudder first order servos: $\frac{1}{.05s+1}$

The stability and control derivatives for the specific configurations were:

Longitudinal Non-Dimensional Derivatives (All angular coefficients in terms of degrees)

	Unaugmented Short Aft Tail
C_{L_o}	1.08
C_{L_α}	.0916
$C_{L_{\delta_e}}$	.0217
$C_{L_{\delta_{DLC}}}$	.003 (1/percent)
C_{D_o}	.115
C_{D_α}	.0093
$C_{D_{\alpha^2}}$	.00046
C_{m_o}	-.0643
C_{m_α}	.01607
$C_{m_{\dot{\alpha}}}$	-.10
C_{m_q}	-.39
$C_{m_{\delta_e}}$	-.026

Lateral-Directional Non-Dimensional Derivatives (All angular coefficients in terms of degrees)

C_{y_β}	-.016
C_{y_p}	0
C_{y_r}	0
$C_{y_{\delta_a}}$	0
$C_{y_{\delta_r}}$	.0033
C_{n_β}	.0021
C_{n_p}	-.0023
C_{n_r}	-.0054
$C_{n_{\delta_a}}$	.00014
$C_{n_{\delta_r}}$	-.0019
C_{ℓ_β}	-.0033
C_{ℓ_p}	-.0082
C_{ℓ_r}	.0038
$C_{\ell_{\delta_a}}$	.0014
$C_{\ell_{\delta_r}}$	.00017

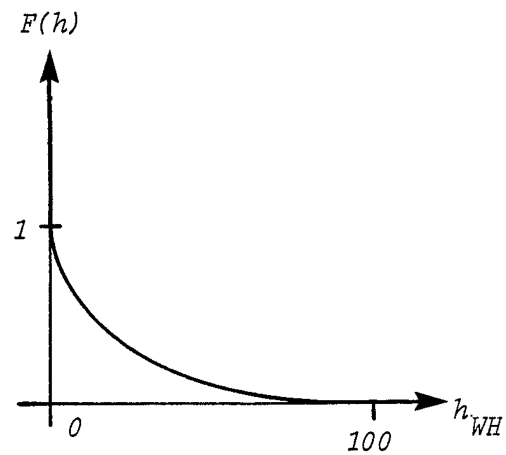
Ground Effect

Typical for large transport aircraft

$$\Delta C_{L_{GE}} = .07\ F(h)$$
$$\Delta C_{D_{GE}} = .016\ F(h)$$
$$\Delta C_{m_{GE}} = -.0038\ F(h)$$

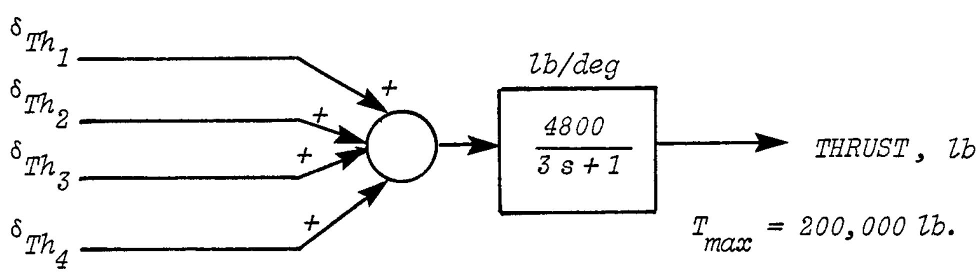
where $F(h)$ is defined from the following:

h_{WH} (ft)	$F(h)$
> 100	0.
90	.02
80	.04
70	.06
60	.08
50	.10
40	.14
30	.20
20	.32
10	.50
0	1.00



Thrust

Thrust was commanded collectively through four throttle handles which produced thrust lagged by a three-second first-order filter.



The control system gains were:

Longitudinal

Alpha Augmentation $K_\alpha = \delta_e/\alpha$, deg/deg	Short Aft Tail K_α
Low (pole at origin)	---
Med $\left(\frac{\omega^2}{n_z/\alpha} = .096\right)$	.85
High $\left(\frac{\omega^2}{n_z/\alpha} = .15\right)$	1.25
Extra High $\left(\frac{\omega^2}{n_z/\alpha} = .24\right)$	---

Pitch Rate Augmentation $K_q = \frac{\delta_e}{q}$, deg/deg/sec $T_q = 1$	Short Aft Tail	
	$K_q(\bar{q})$	$K_q\left(\frac{@150\ KIAS}{\bar{q} = 76.3}\right)$
Low	$42/\bar{q}$	.55
Medium	$80.1/\bar{q}$	1.05
High	$190.8/\bar{q}$	2.5
Extra High with T_q =.5	$397/\bar{q}$	5.2

Alpha Limiting System:

α_{lim} = 6 degrees, equivalent to V = 140 KIAS

$K_{\alpha_{lim}}$ = 2 deg/deg

Lateral-Directional

Feedback Gains	Low Roll Damping (τ_R = .87)
δ_a/β	0
δ_a/p	-1.3
δ_a/r	-1.6
δ_a/ϕ	0
δ_a/δ_{RPC}	- .125
δ_r/β	0
δ_r/p	-1.285
δ_r/r	1.5
δ_r/ϕ	$-2.945 \frac{g}{V} = -.3742$ @ 150 KIAS
δ_r/δ_{AWC}	- .00895

Feel System

In general, the pilots were allowed to select the command gains for each configuration to be evaluated. The evaluations were normally started at the nominal values shown below but for the cases where the pilot requested a command gain change, the value used is noted in the flight/configuration log in Section 4.1.

Pitch Command Gain

$K_{\delta_{EC}}$ (α feedback) = 2.5 deg/in

$K_{\delta_{EC}}$ (q feedback) = 1.25 $\frac{\text{deg/sec}}{\text{in}}$

Roll Command Gain

$K_{\delta_{AW}}$ (τ_R = .87) = 1.5 deg/deg

$K_{\delta_{AW}}$ (τ_R = .44) = 3.0 deg/deg

Yaw Command Gain

$K_{\delta_{RP}}$ = -15. deg/in

NOTE: These are nominal values. See Flight Log in Section 4.1 for values used by each pilot for specific evaluations.

The cockpit controllers consisted of a wheel, column and rudder pedals with the following characteristics:

<u>Pitch</u> –	ω_n (rps)	25.0 or 15.0*
	ζ (–)	.7
	Gradient lbs/in	10.0
	Breakout (lbs)	4.0
	Hysteresis (lbs)	0
<u>Roll</u> –	ω_n (rps)	25.0
	ζ (–)	.7
	Gradient (lbs/deg)	.5
	Breakout (lbs)	2.0
	Hysteresis (lbs)	0
	Max Deflection (deg)	80.0
<u>Yaw</u> –	ω_n (rps)	15.0
	ζ (–)	.7
	Gradient (lbs/in)	100.0
	Breakout (lbs)	3.5
	Hysteresis (lbs)	0

*Pilot A flew all configurations with a 25 rad/sec pitch feel system, Pilot B flew most of his configurations at 15 rad/sec and a few at 25 rad/sec as indicated in the Chronological Flight/Configuration log (Table V in Section 4.1). Pilot B objected to a feel system chatter that occurred with the 25 rad/sec setting when making large force applications.

Section 3
EXPERIMENT MECHANIZATION

3.1 EQUIPMENT

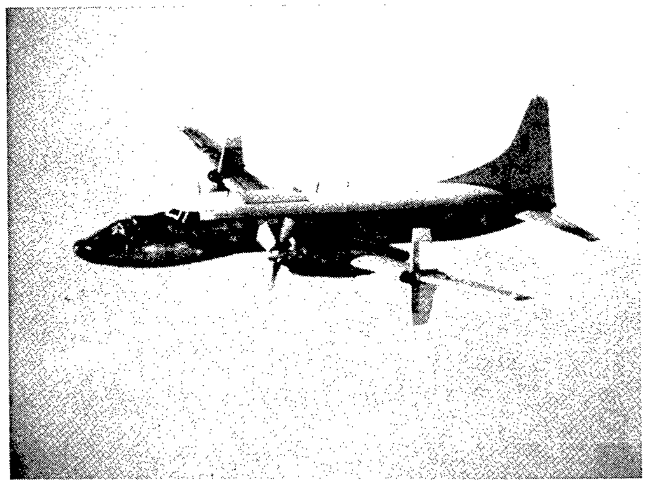
The USAF/Calspan Total In-Flight Simulator (TIFS) was used as the test vehicle in this experiment. TIFS is a highly modified C-131 (Convair 580) configured as a six degree-of-freedom simulator (Figure 6). It has a separate evaluation cockpit forward and below the normal C-131 cockpit. When flown from the evaluation cockpit in the simulation or fly-by-wire mode, the pilot control commands are fed as inputs to the model computer which calculates the aircraft response to be reproduced. These responses, along with TIFS motion sensor signals, are used to generate feedforward and response error signals which drive the six controllers on the TIFS (Figure 7). The result is a high fidelity reproduction of the motion and visual cues at the pilot position of the model aircraft. A detailed description of the TIFS can be found in Reference 2.

3.2 SIMULATION GEOMETRY

The TIFS motion system was configured to reproduce the model's motion at the evaluation pilot's eye point as if the TIFS were positioned as shown in Figure 8. In this sketch, the model is shown in its approximate attitude at touchdown.

Approaches were made to a simulated touchdown with the evaluation pilot at his proper eye height. The TIFS wheels at this altitude were approximately 29 feet above the ground. Altitude was measured by a radar altimeter mounted on the underside of the TIFS fuselage. Equations relating this measured altitude (h_R) to the model wheel height (h_{WH}) and TIFS wheel height (h_T) are given below.

$$h_T = h_R + 21.3 \sin\theta - 6.7 \cos\theta$$
$$h_{WH} = h_R - X_{MGR} \sin\theta - Z_{MGR} \cos\theta$$



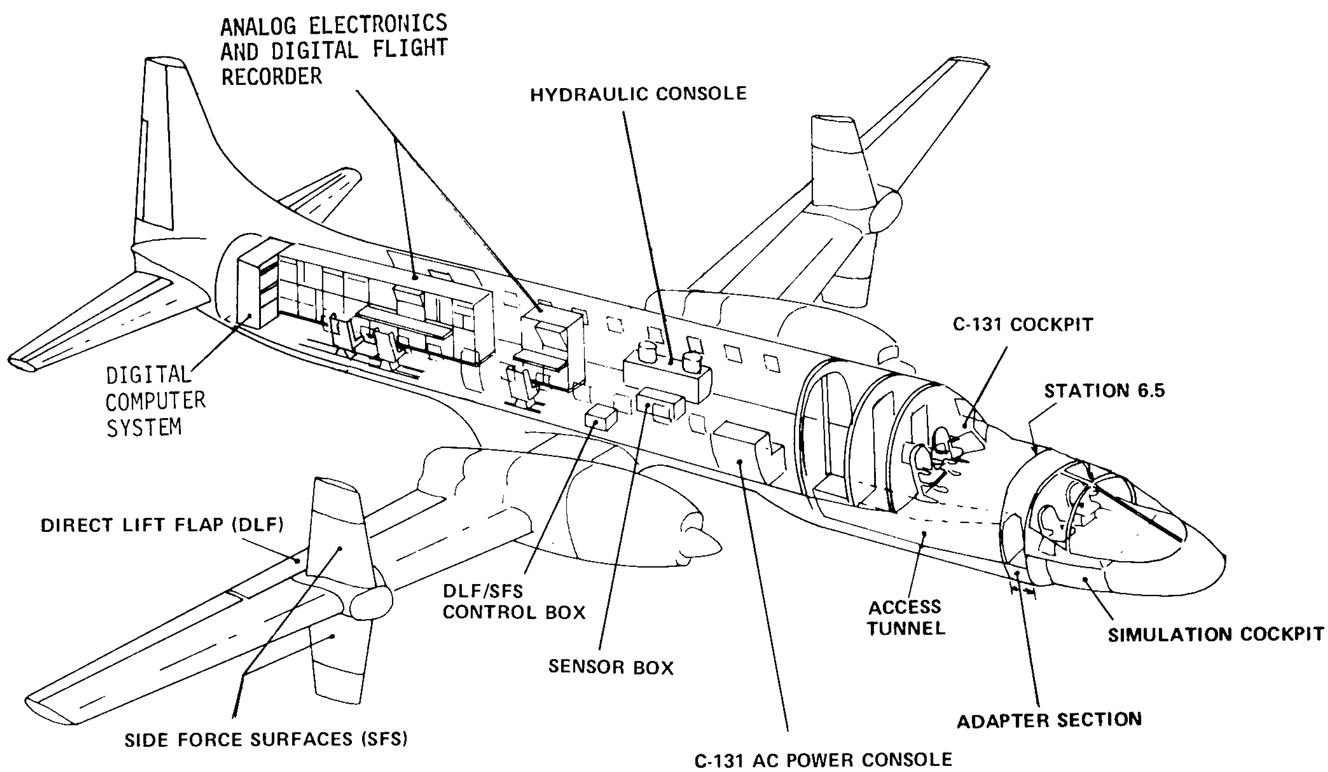


Figure 6. USAF/CALSPAN TOTAL IN-FLIGHT SIMULATOR (TIFS)

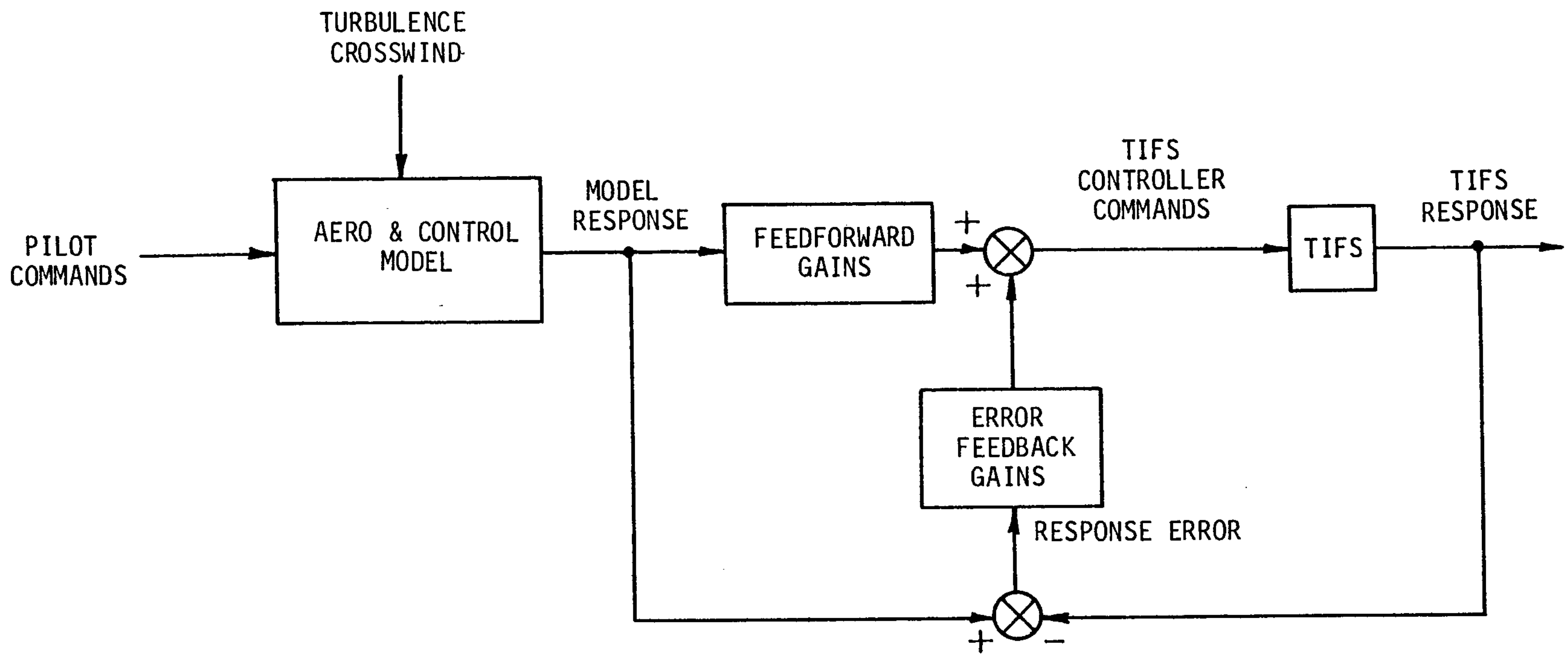


Figure 7. TIFS MODEL FOLLOWING SIMULATION

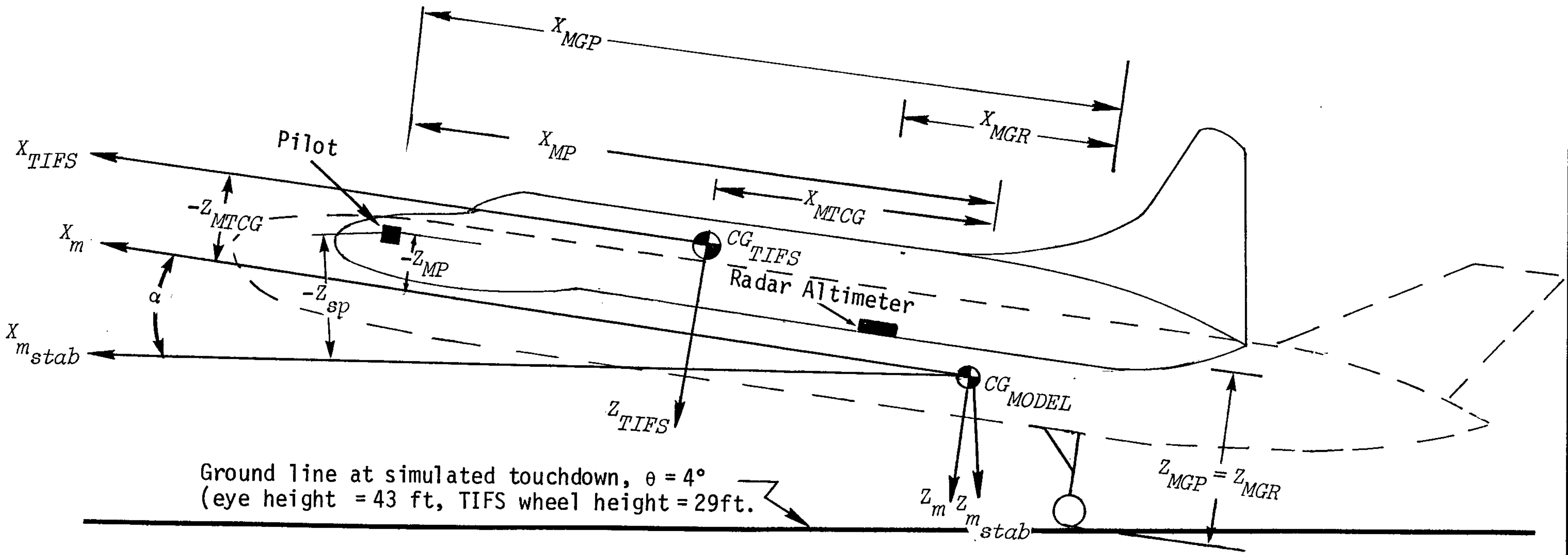


Figure 8. GEOMETRY OF TIFS SUPERIMPOSED ON MODEL

(h_{WH} was altitude called out and displayed to evaluation pilot on his vertical tape). The primary distances of interest are defined in Table II and III.

To obtain responses of the model at the TIFS C.G., a point 33.9 feet aft of the evaluation cockpit, (about which the model following is actually done) transformations were performed on the following model variables to shift them to the TIFS C.G.: $\dot{V}$, α_I, $\dot{\alpha}$, Δn_z, Δn_{z_p}, β_I, $\dot{\beta}$, n_y, n_{y_p}. Once TIFS follows these responses at its own C.G., the pilot's sensed accelerations should also follow even though n_{y_p} and n_{z_p} are not explicitly used in the model following system. This is true because all of the parameters that make up the accelerations ($n_{z_{CG}}$, $n_{y_{CG}}$, $\dot{p}$, $\dot{q}$, $\dot{r}$, V) are matched and the geometry is fixed.

3.3 EVALUATION COCKPIT CONFIGURATION

The evaluation cockpit was configured as illustrated in Figure 9 . The four throttle levers were active and commanded the total thrust of all four engines on the model without any yawing moment effects, i.e., each throttle lever controlled one fourth of the input to the total thrust computation. This provided a large airplane feel without added computational complexity.

The cockpit instruments were generally as shown in Figure 10. Not shown in Figure 10 but included on this program were a horizontal meter between the ADI and the HSI displaying sideslip angle and a vertical meter to the right of the HSI displaying angle of attack. Raw glide slope error was displayed as a vertical bug motion on the left side of the ADI. Raw localizer was shown on the localizer needle on the HSI. Rate of climb and radar altitude were displayed on the tape instrument to the right of the ADI.

TABLE II

PILOT POSITION

(All in body axis except Z_{SP} in stability axis @ $\alpha = 4^{o}$, and in ft)

MP — model C.G. to pilot

$MTCG$ — model C.G. to TIFS C.G.

X_{PCR} — pilot location relative to center of rotation for pitch commands (+) Fwd. (-) Aft

Z_{SP} — pilot location relative to X-stability axis. (-) Above X-axis.

Configuration	X_{MP}	Z_{MP}	X_{MTCG}	Z_{MTCG}	X_{PCR}	Z_{SP}
Base Short Aft Tail (pilot @ 50')	50	-14.5	16.1	-11.7	-10.0	-18
Short Aft (pilot @ 70')	70	-13.1	36.1	-10.3	10.0	-18
Short Aft (pilot @ 110')	110	-10.0	76.1	- 7.2	50.0	-18

TABLE III

MODEL WHEEL POSITION

MGR = model gear to TIFS radar altimeter

MGP = model gear to pilot

Configuration	X_{MGP}	Z_{MGP}	X_{MGR}	Z_{MGR}	h_T ~ TIFS Gear Height @ T.D.	h_{eye}
Short Aft (X_{MP} = 50')	60	34.5	2.4	34.5	29	43
Short Aft (X_{MP} = 70')	80	33.1	22.4	33.1	29	43
Short Aft (X_{MP} = 110')	120	30.0	62.4	30.1	29	43

Figure 9. TIFS SIMULATION COCKPIT

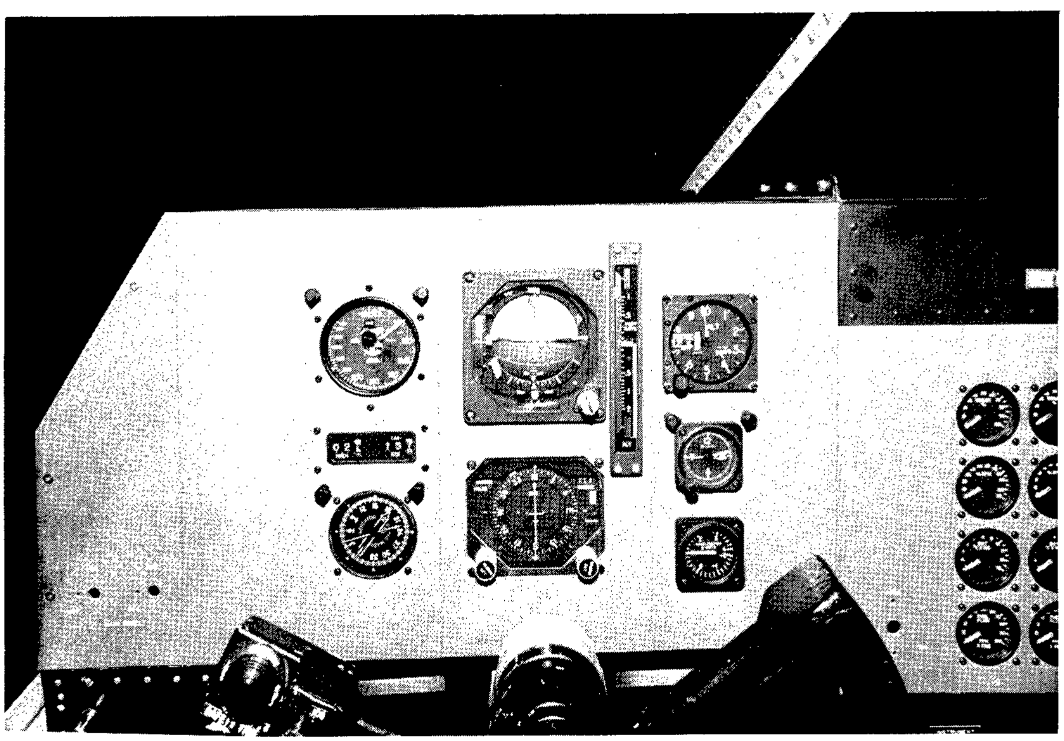


Figure 10. CAPTAIN'S INSTRUMENT PANEL IN EVALUATION COCKPIT

Pitch and roll trim controls were combined in a wheel-mounted thumb switch. The rudder trim control was a switch on the center console.

A Collins flight director,installed in the TIFS,was used during the IFR portion of the evaluation task and drove the command bars on the ADI.

3.4 EVALUATION PROCEDURE AND TASK DESCRIPTION

The subject aircraft in these evaluations was a very large Class III military transport which was evaluated in the terminal area flight phase.

The evaluation tasks consisted of the following elements:

- Up-and-away airwork (Specific evaluations of up-and-away tasks were eliminated after the second evaluation flight to allow more time for approaches. Thereafter, the pilot was allowed to briefly sample the up-and-away characteristics of the configuration before the first approach and on the downwind leg between approaches.)
  - Trimmability
  - Maneuvering about level flight
  - Airspeed changes
  - Altitude changes
- Specific landing approaches aided by flight director information:
  - Localizer offset
  - Crosswind
  - Turbulence
  - Precise touchdown parameters

The landing approach evaluation task, following the brief airwork, consisted of the following:

Precision tracking of the ILS beam, preceded by a "capture" segment beginning beyond the outer marker and at an angle between 30° and 45° to the beam. The evaluation pilot was under a hood during the simulated IFR approaches until the final portion starting from the middle marker at an altitude of approximately 300 feet down to the completion of the task. This latter portion of the approach, including flare and a simulated touchdown at proper model eye height of 43 feet, was to be completed visually. Precise simulated touchdowns were to be attempted. Acceptable landings were defined to be within a 1000 foot zone centered 1000 ft from the threshold of the runway with a low sink rate (<5 ft/sec). Touchdown was signaled by a tone over the intercom and a signal light.

The task was made more difficult with the addition of localizer offsets and artificial or natural atmospheric disturbances of crosswinds and turbulence.

The localizer offset was a constant 1.5 degree or 1.2 dot <u>angular</u> offset that translated to a 400 ft lateral error at the breakout altitude of 300 feet. This forced the pilot to make lateral-directional corrections so all of his attention was not kept on the longitudinal task.

The crosswind was added or canceled out with the TIFS sideslip mismatch capability. This capability is limited to a β of .1 radian, equivalent to a 15 knot change in the apparent crosswind at an airspeed of 150 knots.

Turbulence was also added to disturb the model's response. It was desired to have a light to moderate level of turbulence during each evaluation. When the natural level of turbulence was at this level, it was measured and introduced into the model's aerodynamic equations through α_g and β_g components added to the inertial α_I and β_I signals to form the total signals α_T and β_T. When the natural level of turbulence was less than this, artificially generated turbulence was introduced into the model. The turbulence signals recorded on an FM recorder are filtered Gaussian white noise. The filtered noise approximates a Dryden model of turbulence at one specific

altitude and speed. The filter characteristics were chosen to duplicate the power spectrum of turbulence at 330 feet and 150 KIAS. The α or vertical turbulence had a break frequency of .75 rad/sec (.12 Hz) and the β or lateral turbulence had a break frequency of .25 rad/sec (.04 Hz). The standard deviation of the artificial turbulence components were set at the following values to simulate moderate turbulence:

$$\sigma_{\alpha_g} = 1.13 \text{ deg } (5 \text{ ft/sec})$$

$$\sigma_{\beta_g} = 2.0 \text{ deg } (8.7 \text{ ft/sec})$$

Usually three approaches were flown for each evaluation of a configuration. The first was a long ILS approach as previously described. The 400 foot localizer offset was inserted. Crosswinds were canceled to let the pilot concentrate on the longitudinal control in flare and touchdown. The second and third approaches were usually visual, starting from an altitude of approximately 1000 feet above the ground on the downwind leg. The second approach had no localizer offset but had the 15-knot crosswind inserted. The third approach had both localizer offset (if it was an ILS) and the 15-knot crosswind inserted. All approaches had turbulence added to approximate a moderate level of intensity. The localizer offset and crosswinds were randomly alternated left or right. The evaluation pilot was allowed to choose a fourth approach at his discretion.

3.5 PILOTS AND EVALUATION SUMMARY

Two evaluation pilots participated in this flying qualities investigation. Both of them are Calspan Research Pilots with very extensive experience as flying qualities evaluation pilots. They are also flying qualities instructors at the Air Force and Navy Test Pilot Schools, demonstrating stability and control characteristics with Calspan's variable stability aircraft. Pilot A's flight experience of 7500 hours includes 750 hours in Class III aircraft. He was also an evaluation pilot in Calspan's space shuttle orbiter simulations. Pilot B's flight experience of 5500 hours has been in a wide variety of aircraft.

The two pilots performed a total of 90 evaluations of 55 different configurations (12 of which dealt with the Short Aft Tail configurations) during the evaluation phase of the flight program. A total of 260 approaches were made. Twenty-four flights of approximately two hours each were flown. The distribution of flights and evaluations between the pilots was as follows:

	Pilot A		Pilot B	
	Total	Short Aft Tail	Total	Short Aft Tail
Flights	18	4	6	2
Evaluations	62	12	28	8
Configurations	53	10	25	7
Approaches	186	38	74	21

3.6 PILOT COMMENT CARD AND RATING SCALES

The evaluation pilots were briefed on the general experiment purposes and evaluation procedures before they flew. They were informed as to whether longitudinal or lateral-directional handling qualities were the prime subject of an individual evaluation. In addition, they were told which of the basic aircraft configurations (Long Aft Tail, Canard, Short Aft Tail) they were flying. It was believed that their control technique might have had to be changed for each one,and that they should know their location with respect to the main landing gear.

The pilots were asked to make brief comments on the configuration after each approach as the safety pilots were setting up the TIFS for the next approach. These comments were informal and covered initial impressions. After all of the approaches for an evaluation were completed, the evaluation pilot made his formal comments and pilot ratings. His comments followed the Comment Card shown in Figure 11. If the configuration was a lateral-directional evaluation, he also gave comments on the points shown on the B section of the Comment Card. After the formal comments, the pilot gave one Cooper-Harper rating (Figure 12) that covered all flying qualities in the landing approach task. In addition, a Pilot-Induced Oscillation (PIO) Tendency Classification (Figure 13) was given.

A. LONGITUDINAL CONFIGURATIONS

1. Feel
   - forces, displacements?
   - pitch sensitivity? - trim?
2. Pitch attitude response to inputs <u>required to perform task</u>
   - initial response
   - predictability of final response
   - special pilot inputs?
   - tendency towards PIO?
3. Airspeed control
4. Approach performance
   - ILS: glideslope, localizer, throttle
   - visual approaches (sidestep maneuver)
5. Flare and touchdown performance
   - problems? - any special control techniques?
6. Differences between approach and landing tasks
   - significant? - most difficult task?
7. Effects of turbulence/wind
8. Lateral-directional characteristics: a factor in evaluation?
9. Summary (brief)
   - major problems - good features
10. Cooper-Harper Pilot Rating (separate ratings for different tasks if possible) - PIO rating.

B. LATERAL-DIRECTIONAL CONFIGURATIONS

1. Roll control authority
2. Roll control sensitivity
3. Roll response in general
4. Roll tendency to overshoot
5. Heading response
   a. turn entry
   b. roll out of turn
6. Tendency to sideslip for roll maneuvers
7. Rudder control
   a. power
   b. sensitivity
8. Tendency of A/C to maintain bank angle
9. Roll-pitch control harmony
10. Other comments – ride quality
    – initial accelerations vs. steady state
    – turbulence effects on ride quality
    – magnitude of inputs before accelerations become unsatisfactory or unacceptable

Figure 11. PILOT COMMENT CARD, APPROACH AND LANDING

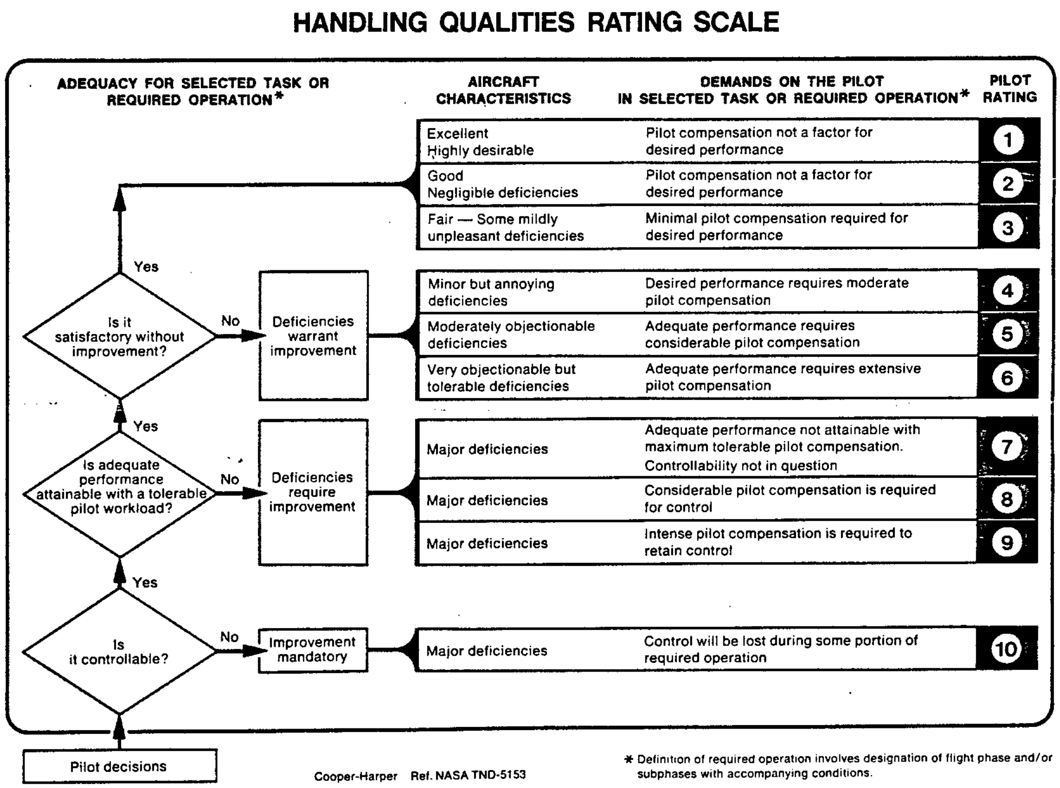


Figure 12. COOPER-HARPER HANDLING QUALITIES RATING SCALE

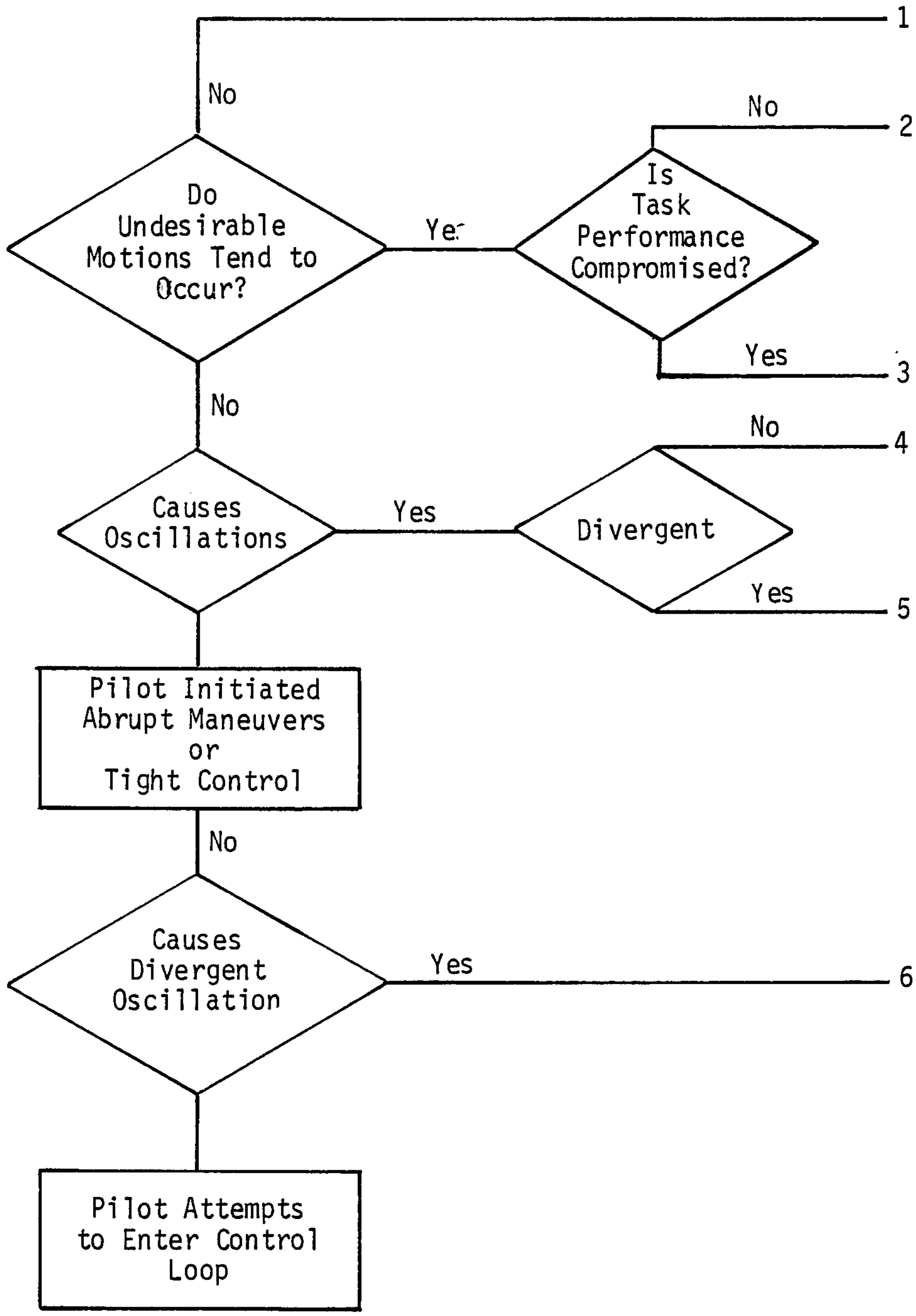


Figure 13. PIO TENDENCY CLASSIFICATION SCALE

Pilot commentary and ratings were recorded on a tape recorder in flight. These comments were transcribed and are available from Calspan files. Summaries for the Short Aft Tail configurations are presented in Appendix III.

3.7 DATA RECORDING

A 58-channel digital recorder was used to record signals of interest. These included:

1. Pilot command inputs
2. Control surface motions
3. Aircraft states – model and TIFS
4. Localizer and glideslope deviation
5. Radar altitude
6. Turbulence inputs

A specific list of recorded variables is presented in Appendix VI.

3.8 MODEL-FOLLOWING VERIFICATION

Samples of model-following responses are shown in Figures 14 through 17. These include pitch and roll automatic steps and typical approach records. The .06 sec and .12 sec model-following delay in pitch rate and roll rate, respectively, can be seen. The longitudinal approach record shows a PIO developing with the Short Aft Tail configuration. Most of the higher frequency differences between the model and TIFS responses are due to natural turbulence which was not inserted into the model on these records. There were some errors in angle of attack model-following, especially in turns, which was later traced to air data computational errors in the TIFS sensor system. However, these problems did not affect the model following of the primary variables of pitch rate and normal acceleration. Early in the evaluation program, due to the sensor problem, the model was given an erroneous low dynamic pressure at the system engage point. This forced the model to trim at a slightly higher angle of attack than desired. This would put the model further aft on the backside of its power required curve. This complicated the airspeed control task

on a few approaches which was already difficult due to slow model thrust response. The evaluation pilots noted the approaches on which they had these extra airspeed control problems and attempted to ignore these effects when rating the configurations.

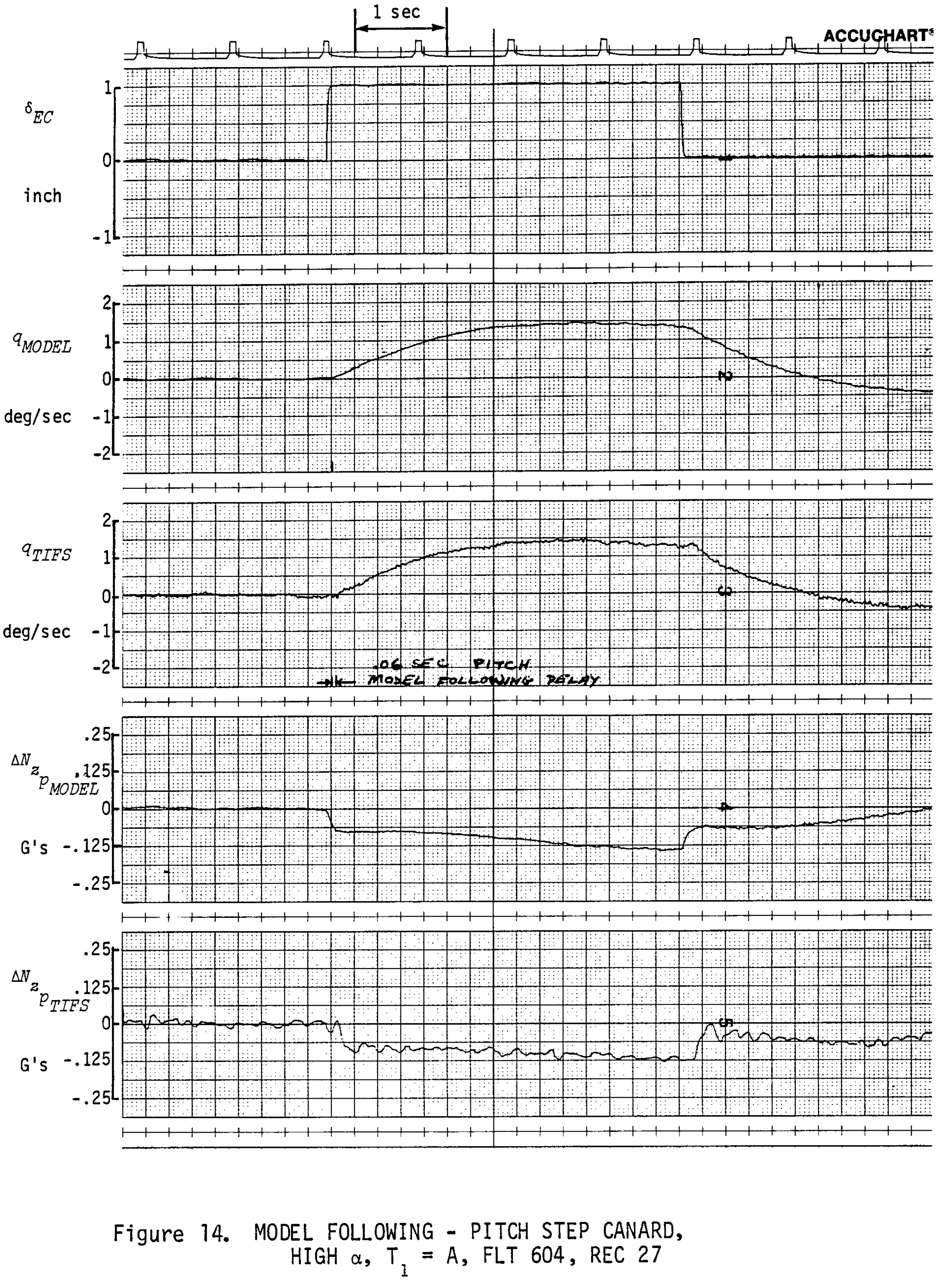


Figure 14. MODEL FOLLOWING - PITCH STEP CANARD, HIGH α, T_1 = A, FLT 604, REC 27

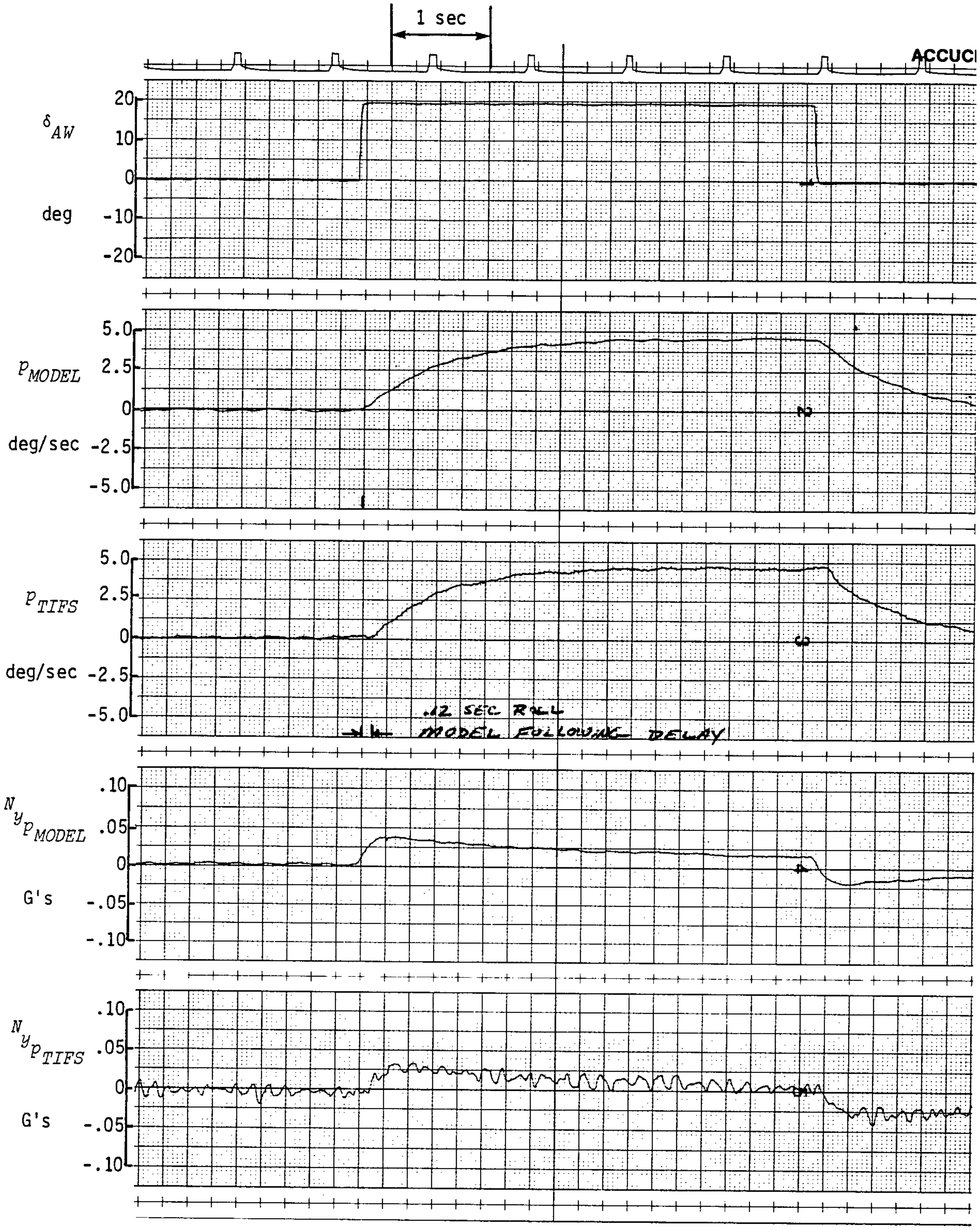


Figure 15. MODEL FOLLOWING ROLL STEP τ_R = .87, Z_{SP} = 18 FT, T_1 = A, FLT 604, REC 28

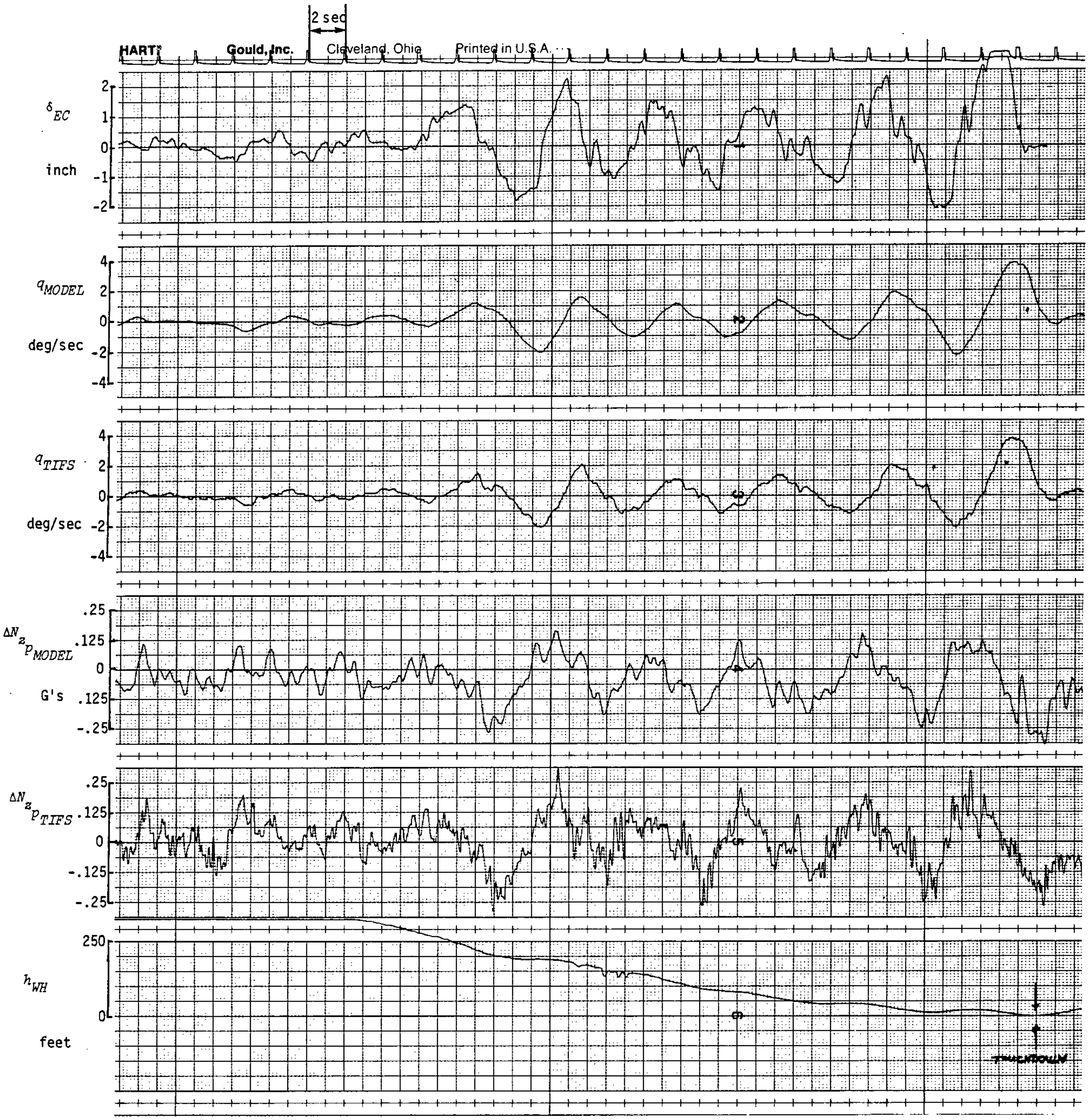


Figure 16. MODEL FOLLOWING - LONGITUDINAL ON APPROACH (INCLUDES PIO) SHORT AFT TAIL, MED α, T_1 = B, FLT 615, REC 31

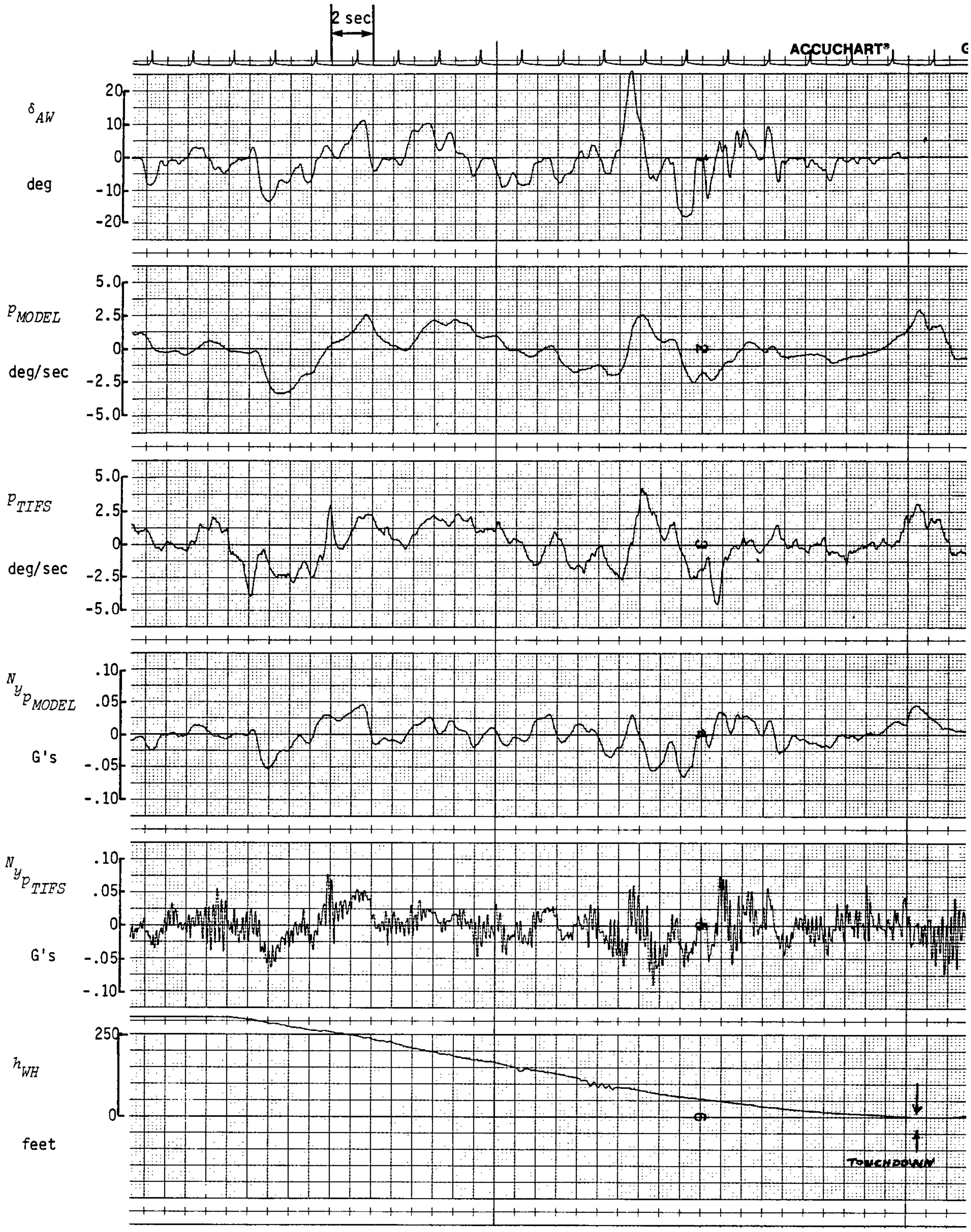


Figure 17. MODEL FOLLOWING - LATERAL/DIRECTIONAL ON APPROACH, τ_R = .87, Z_{SP} = -18 FT, FLT 615, REC 10

Section 4
EXPERIMENT RESULTS AND ANALYSIS

4.1 INTRODUCTION

The results of the Large Airplane flying qualities experiment covering the shuttle-like Short Aft Tail configuration are presented in this section. The data obtained from the experiment are in the form of pilot ratings and pilot comments. Correlations of pilot rating with the various experimental variables are presented. Pitch attitude, pilot/aircraft control-loop analysis was performed to correlate with the data. A multi-loop analysis of pitch attitude and altitude control is also presented. Finally, a discussion of the turbulence response is given.

The pilot comment summaries from the evaluated configurations were too lengthy to include in this section and are presented in Appendix III. The appendices also contain additional data correlations and analyses which were carried out. These include equivalent system analysis in Appendix V-A, time history criteria for pitch rate response in Appendix V-B, and open-loop aircraft and aircraft plus uncompensated pilot analysis in Appendix V-C and V-D.

As an aid in following the analysis in this section, a Configuration-Flight Index, along with a Chronological Flight/Configuration Log (Tables IV and V) are presented. Only the Short Aft Tail configurations are shown. This will allow one to determine on which flight a specific configuration was flown, pilot, order of configurations flown, number of approaches, pilot ratings, and any special remarks for that configuration presentation. In addition, Tables VI and VII present a listing of the pilot ratings and PIO ratings in a summary form.

TABLE IV

CONFIGURATION - FLIGHT INDEX

Configuration (All longitudinal config's flown with $\tau_R = .87$, $Z_{sp} = -18'$, $T_{1_{roll}} = A$)		Flight/Pilot Level of Delay (T_1) A	B	C
Short Aft Tail	Med α	619/A	615/B,618/A	
	High α	615/B,618/A 630/A with DLC 630/A	619/A	
	Med q	619/A		
	High q	615/B,619/A 630/A,631/B, with DLC 629/A		631/B (T_1=.35)
	High q (X_{mp} = 70')	629/A,631/B		
	High q (X_{mp} = 110')	629/A,631/B		
	Ex-High q	631/B		

TABLE V

CHRONOLOGICAL FLIGHT/CONFIGURATION LOG

FLT	1980 DATE	CONFIGURATION	PILOT	PR	PIOR	APP'S	OTHER REMARKS
							All at Niagara and nominal gearings except as noted.
615	7/31	Short aft, high α, $T_1 = A$	B	10	4	1-ILS,3-VIS	
		Short aft, med α, $T_1 = B$	B	10	6	1-ILS,1-VIS	
		Short aft, high q, $T_1 = A$	B	6	3	1-ILS,1-VIS	Pilot B flew with 15 rad/sec pitch feel system.
618	8/4	Short aft, high α, $T_1 = A$	A	9	5	1-ILS,2-VIS	1.3 x nominal gearing.
		Short aft, med α, $T_1 = B$	A	10	5	1-ILS,1-VIS	1.3 x nominal gearing.
619	8/4	Short aft, high α, $T_1 = B$	A	10	6	1-ILS,2-VIS	2.0 x nominal gearing.
		Short aft, med α, $T_1 = A$	A	10	5	1-ILS,2-VIS	No G/S guidance.
		Short aft, med q, $T_1 = A$	A	9	4	1-ILS,2-VIS	2 x nominal gearing, at Rochester.
		Short aft, high q, $T_1 = A$	A	9	4	1-ILS,2-VIS	at Rochester
629	8/12	Short aft, high q, $T_1{=}A, X_p{=}70'$	A	5	1	1-ILS,2-VIS	at Buffalo.
		Short aft, high q, $T_1{=}A, X_p{=}110'$	A	4-1/2	1	1-ILS,3-VIS	at Buffalo.
		Short aft, high q, $T_1{=}A$, DLC	A	5	2	1-ILS,4-VIS	
630	8/13	Short aft, high q, $T_1 = A$	A	5	3	1-ILS,2-VIS	1.5 x nominal gearing.
		Short aft, high α, $T_1 = A$	A	8	4	1-ILS,2-VIS	1.3 x nominal gearing.
		Short aft, high α, $T_1{=}A$, DLC	A	6	3	1-ILS,3-VIS	1.3 x nominal gearing.

TABLE V (CONT'D)

CHRONOLOGICAL FLIGHT/CONFIGURATION LOG

FLT	1980 DATE	CONFIGURATION	PILOT	PR	PIOR	APP'S	OTHER REMARKS
							All at Niagara and nominal gearings except as noted.
631	8/14	Short aft, high q, T_1=A, X_p=70'	B	8	3	1-ILS,2-VIS	
		Short aft, high q, T_1 = .35	B	9	4	1-ILS,2-VIS	Equivalent shuttle delay/lag
		Short aft, Ex-Hi q, T_1 = A	B	4	2	1-ILS,1-VIS	
		Short aft, high q, T_1=A, X_p=110'	B	3	1	1-ILS,2-VIS	
		Short aft, high q, T_1 = A	B	4	2	1-ILS,1-VIS	at Buffalo, 1.5 x nominal gearing.

TABLE VI

COOPER-HARPER PILOT RATINGS (PR)

CONFIGURATION** (All longitudinal config's flown with $\tau_R = .87$, $Z_{sp} = -18'$, $T_{1_{roll}} = A$)		LEVEL OF DELAY (T_1) A		B		C	
		Pilot A	Pilot B	Pilot A	Pilot B	Pilot A	Pilot B
Short Aft $X_{mp}=50'$ $X_{PCR}=-10'$	Med α	10 (DLC)		10	10		
	High α	9,8,6	10	10			
	Med q	9 (DLC)					
	High q	9,5,5	6,4				9 (T_1=.35)
	High $q\begin{pmatrix}X_{mp}=70'\\X_{PCR}=10'\end{pmatrix}$	5	8*				
	High $q\begin{pmatrix}X_{mp}=110'\\X_{PCR}=50'\end{pmatrix}$	4-1/2	3				
	Ex-Hi q		4				

*First configuration flown after one week non-flying, said may have been biased against all short aft configurations at start of flight.

**Pitch feel system: Pilot A ~ ω_n = 25 rad/sec
Pilot B ~ ω_n = 15 rad/sec

TABLE VII

PILOT-INDUCED OSCILLATION RATINGS (PIOR)

CONFIGURATION** All longitudinal config's flown with $\tau_R = .87$, $Z_{sp} = -18'$, $T_{1_{roll}} = A$)		LEVEL OF DELAY (T_1)					
		A		B		C	
		Pilot A	Pilot B	Pilot A	Pilot B	Pilot A	Pilot B
Short Aft	Med α	5		5	6		
	High α	(DLC) 5,4,3	4	6			
	Med q	4					
	High q	(DLC) 4,3,2	3,2				4 (T_1=.3
	High q (X_{mp}=70')	1	3				
	High q (X_{mp}=110')	1	1				
	Ex-Hi q		2				

**Pitch feel system: Pilot A ~ ω_n = 25 rad/sec
Pilot B ~ ω_n = 15 rad/sec

4.2 PILOT RATINGS VERSUS EXPERIMENT VARIABLES

The primary variables in the Large Airplane experiment were:

- Pilot location with respect to pitch center of rotation.
- Augmentation schemes — α-feedback and q-feedback with proportional plus integral command to yield attitude hold.
- Level of augmentation.
- Time delay — produced by model-following lags and inserted prefilters and pure time delays.

The effect of these parameter variations on pilot ratings are shown in Figures 18 through 24. On some of these figures, results from the Long Aft Tail and Canard configurations are shown to highlight contrast between the Short Aft Tail configurations and more conventional configurations.

The total effective time delay, t_1, was measured by the maximum slope intercept method from computed time histories. It includes the feel system, added lags or delays, model control system, airplane model, and TIFS model following delay. Appendix V-B presents a tabulation of t_1 for the pitch configurations.

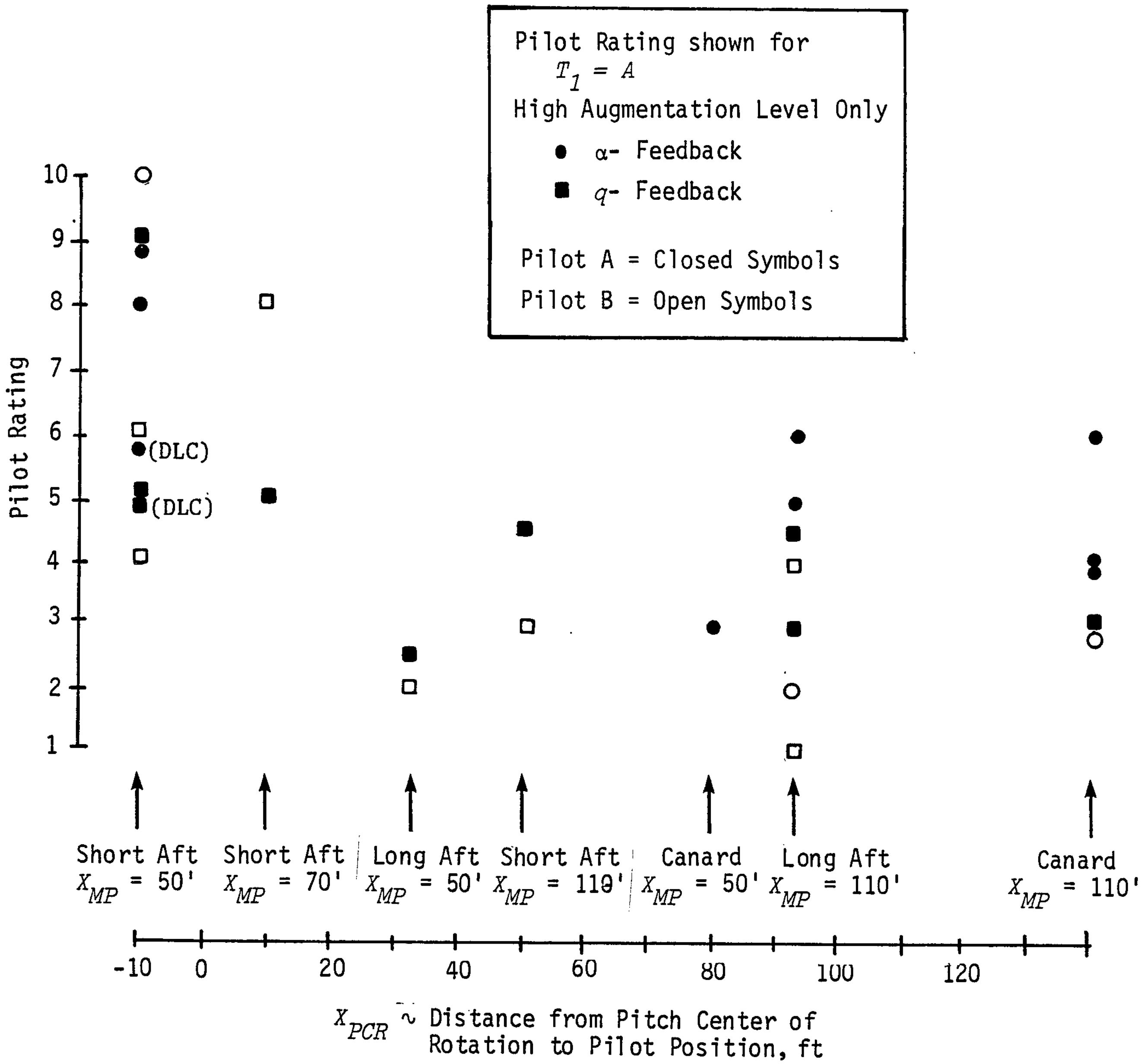


Figure 18. PILOT RATING VS PILOT POSITION - CENTER OF ROTATION (X_{PCR})

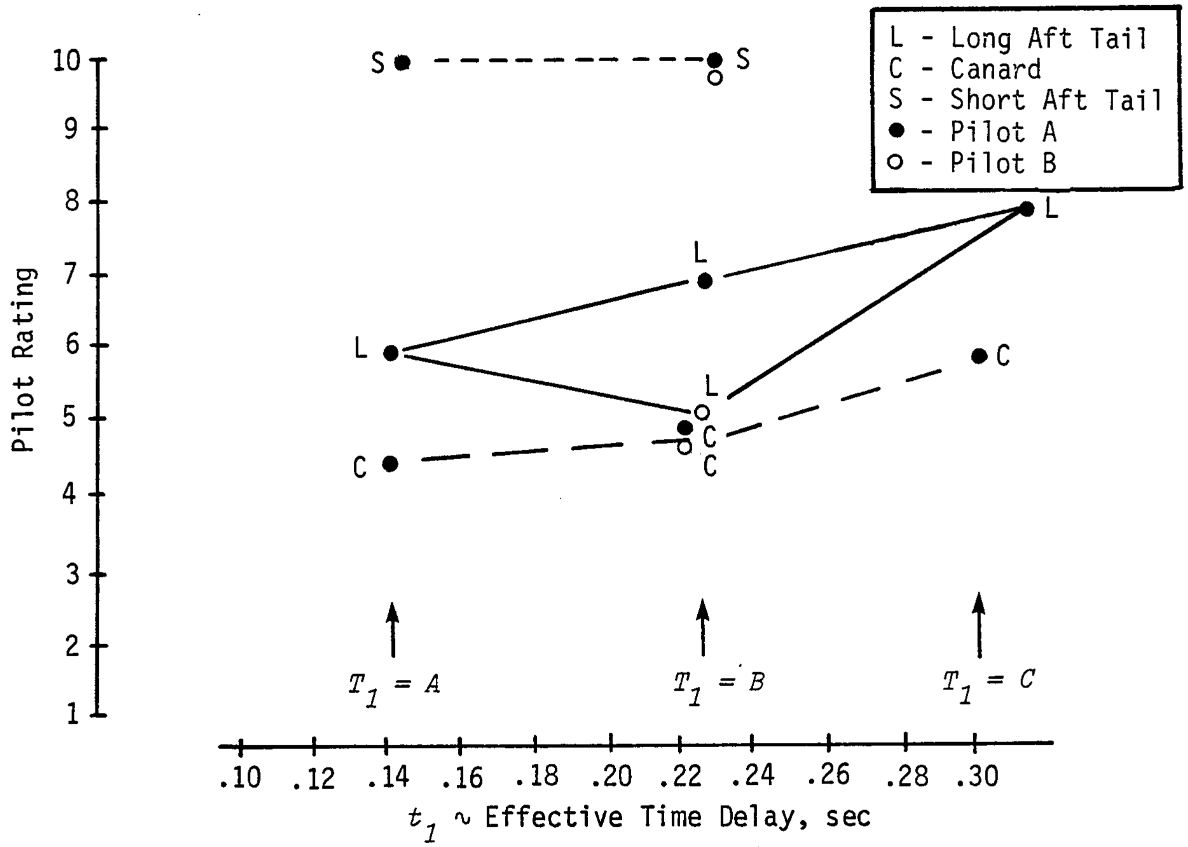


Figure 19. PILOT RATING VS EFFECTIVE TIME DELAY - MED. α FEEDBACK

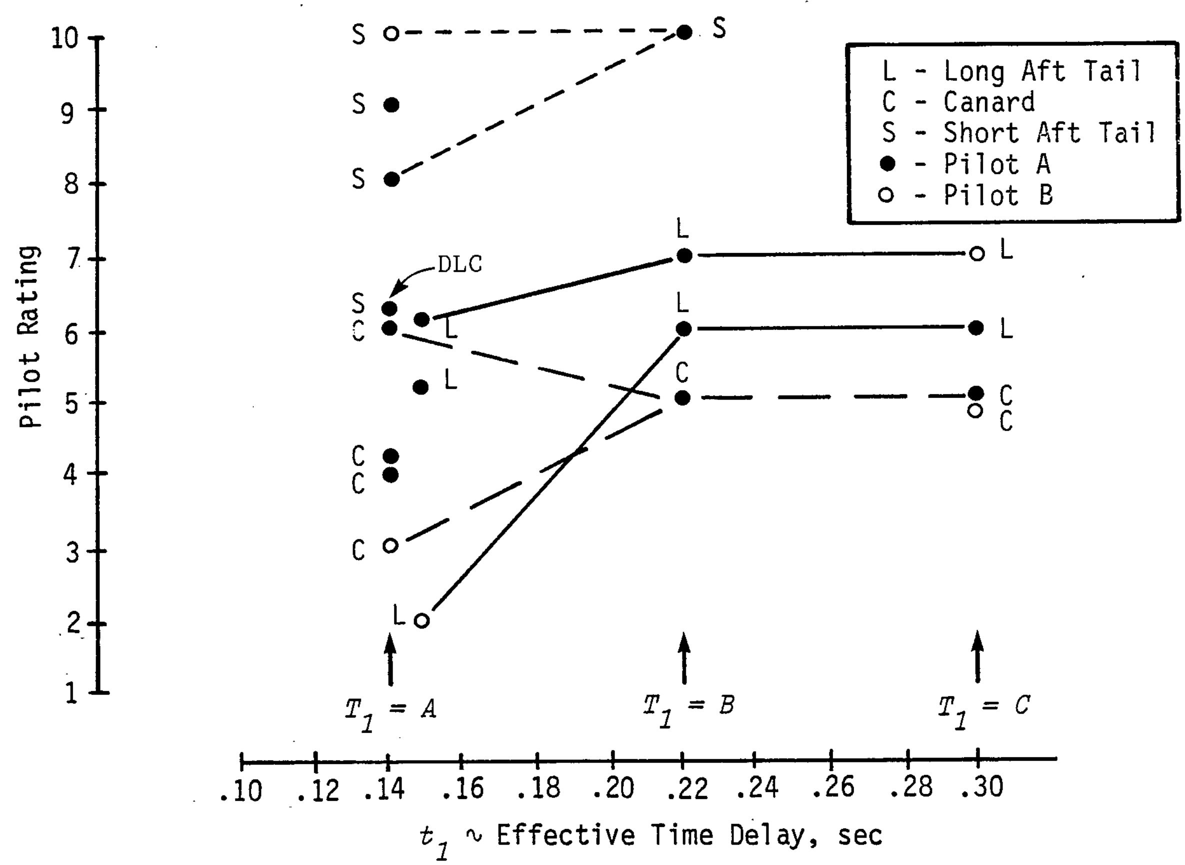


Figure 20. PILOT RATING VS EFFECTIVE TIME DELAY - HIGH α FEEDBACK

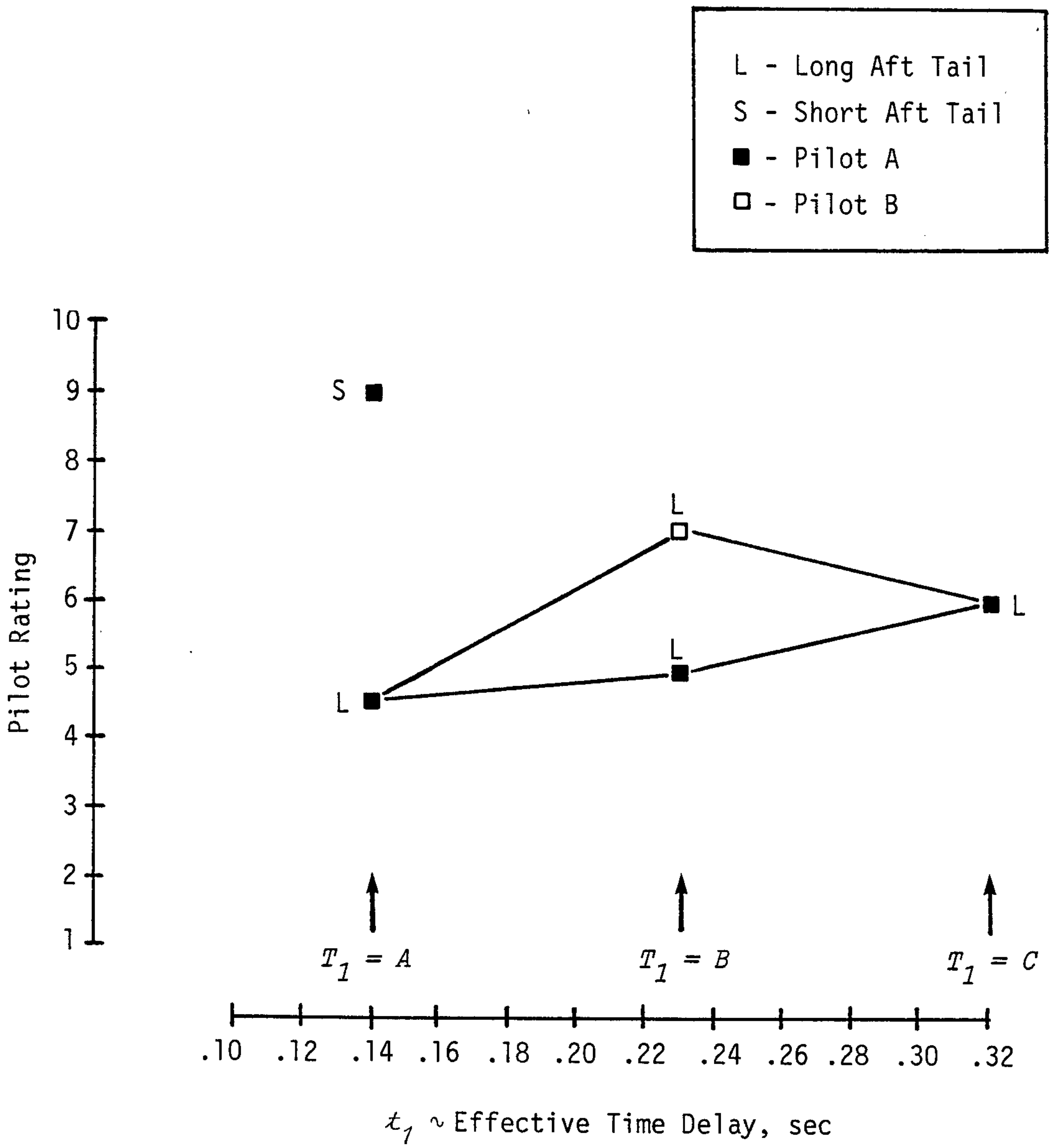


Figure 21. PILOT RATING VS EFFECTIVE TIME DELAY - MED q FEEDBACK

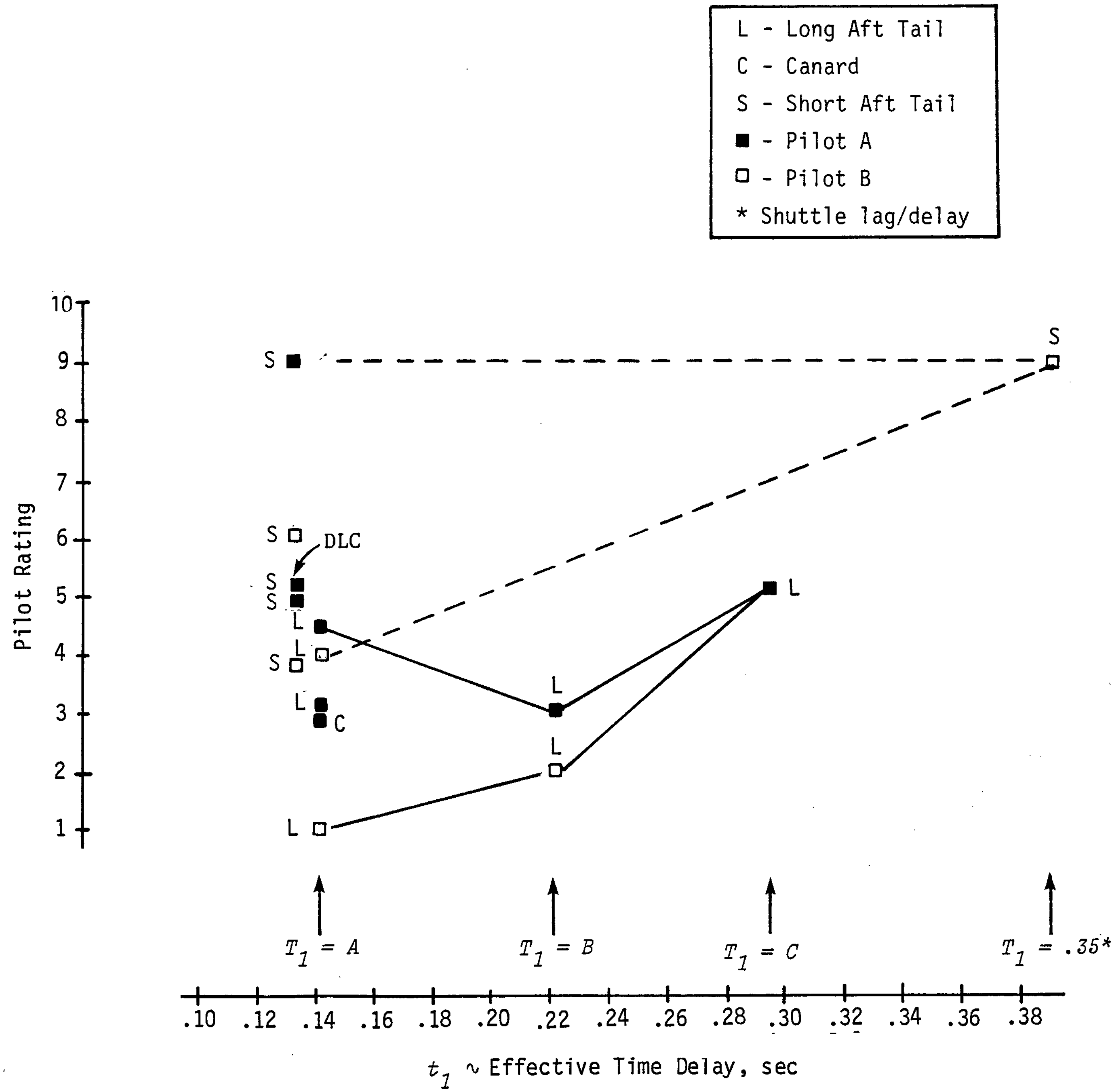


Figure 22. PILOT RATING VS EFFECTIVE TIME DELAY - HIGH q FEEDBACK

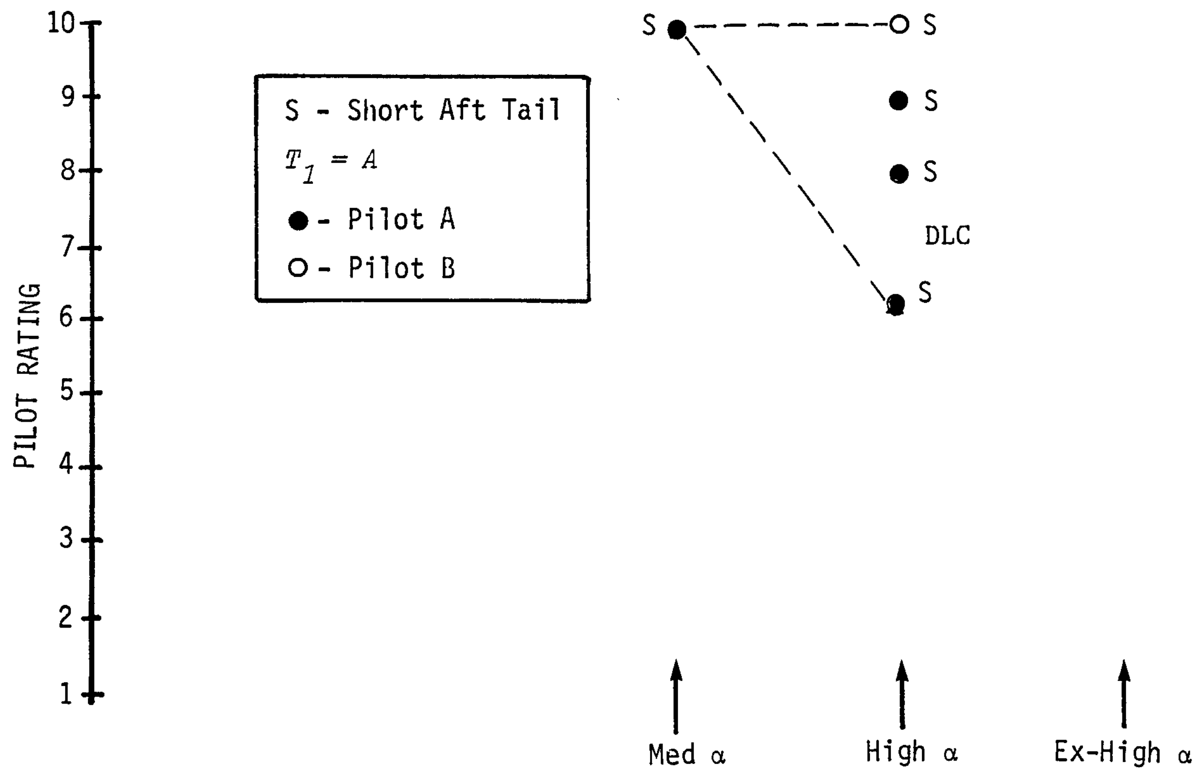


Figure 23. PILOT RATING VS LEVEL OF AUGMENTATION -α FEEDBACK

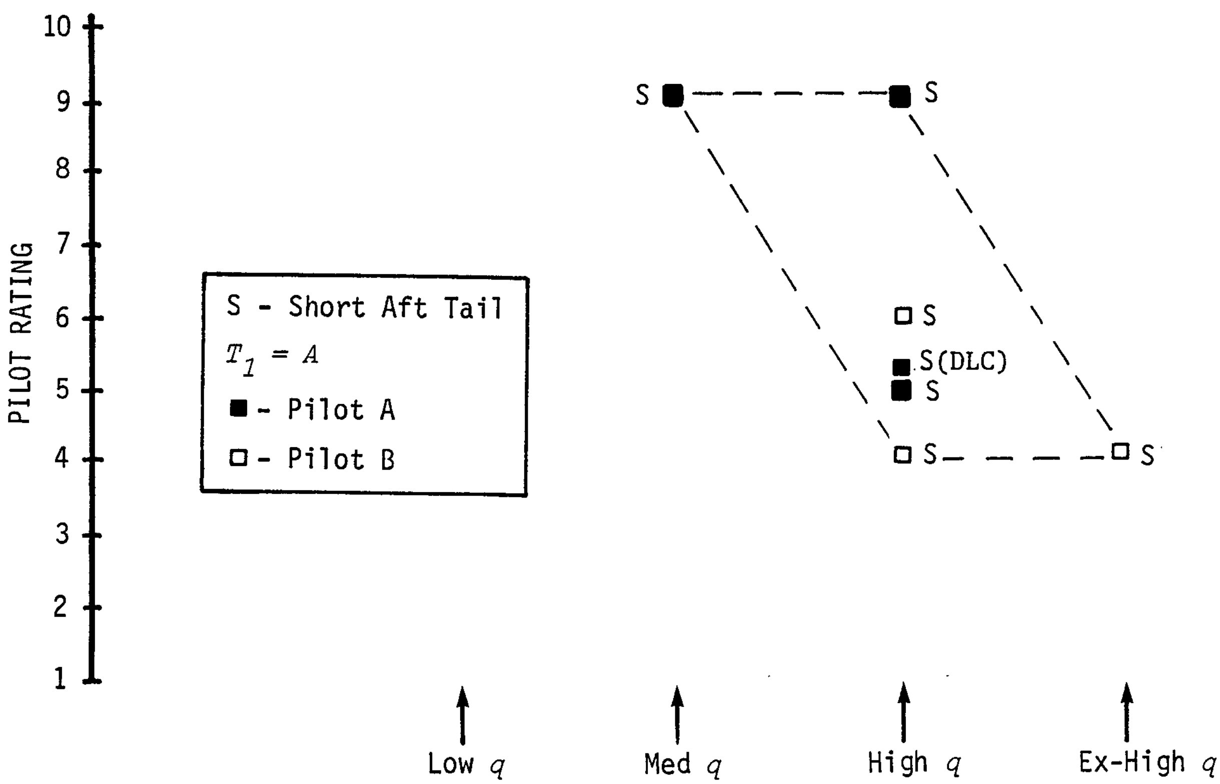


Figure 24. PILOT RATING VS LEVEL OF AUGMENTATION -q FEEDBACK

4.2.1 Longitudinal Results

One point that should be brought out before going into the longitudinal results is that many of the test points were down-rated for airspeed control problems due to slow thrust response and backside operation, and not pitch dynamics. There were very few cases in the overall experiment where pilot ratings of better than 3 were received even when there were no problems with pitch control. There may have been a one to two point degradation in pilot rating due to this speed control problem.

Figure 18 shows how pilot ratings were affected by the variation of pilot position with respect to pitch center of rotation. The pilot position was changed from ten feet aft of the center of rotation to 50 feet forward in the Short Aft Tail configuration. Data is also shown for the Long Aft Tail and Canard configurations. Data is presented in this figure for only the high level of augmentation cases and with time delay level $T_1 = A$. There is a definite trend towards better ratings as the pilot is positioned further forward of the center of rotation. This is more strikingly shown on some of the following figures where pilot ratings versus effective time delay and levels of augmentation are presented.

This large variation in pilot ratings for configurations that were essentially the same except for pilot position is partly the effect of visual perception of rate of climb and altitude at the pilot position when near the ground and partly the effect of normal acceleration felt by the pilot. These cues are the normal acceleration at the pilot station and essentially the integrations of it. Normal acceleration at the pilot station is defined by:

$$N_{z_p} = N_{z_{c.g.}} + \frac{X_{MP}\dot{q}}{g}$$

Figure 25 presents the normal acceleration and altitude step responses for the three pilot locations, each for the High q-augmentation level. The distances from the center of rotation to pilot position are +50, +10, -10 feet, respectively, for these configurations. It can be seen that the +50 configuration has a much larger initial N_{z_p} kick than the +10 configuration. The

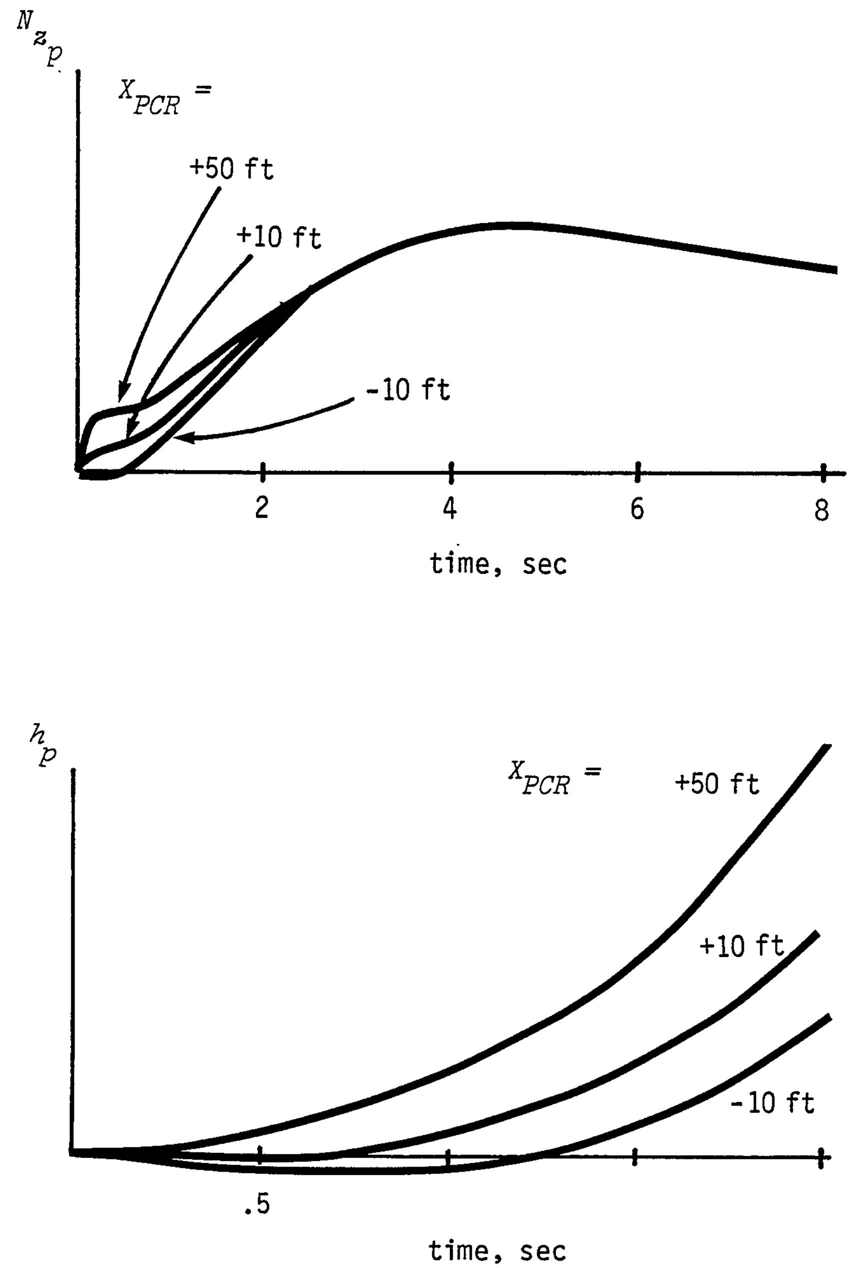


Figure 25. NORMAL ACCELERATION AND ALTITUDE AT VARIOUS PILOT STATIONS IN SHORT AFT TAIL CONFIGURATION, HIGH α AUGMENTATION, T_1 = A

-10 configuration produces a non-minimum phase shape with the response initially going slightly negative before going positive and matching the other responses near three seconds into the time history. It is near one and one-half seconds into the response before the pilot can actually see his altitude change. The pilot comments clearly indicate that the pilots perceived this. With the +50 configuration, the pilots found they could fly the airplane more "naturally," the response felt more crisp and fine corrections in sink rate near touchdown were more easily made. The better perceived control over rate of sink, especially in the flare, overcame some of the problems related to the low short period frequency. The -10 ft configuration was described as "very sluggish and delayed" even with the high augmentation levels and no extra lags or delays added. The ILS and VFR tracking away from the ground was described as "all right" but as soon as the pilot acquired outside cues for references in flare and touchdown, the control deteriorated. Many times, PIO's resulted. Comments indicated precise control of sink rate near touchdown was very poor or impossible. All of the pilot's attention was devoted to the altitude and rate of sink task with the touchdown point and lateral-directional task ignored many times.

The effect of time delay on pilot ratings had the expected overall trend (Figure 19-22). As the effective time delay (measured from the maximum slope intercept method – see Appendix V-B) increased from a level near .14 seconds to .35 seconds, pilot ratings degraded. The degree of degradation exhibited in the overall experiment was less than expected based on experience in the landing experiment of Reference 6. The degrading effect of time delay may not be as strong due to the low level of agility demanded by the pilots in this experiment. The task was to land a one-million pound transport aircraft with low turbulence response and strong ground effect. These characteristics and the low agility demanded by the pilot combine to yield an aircraft which can be landed using a significantly different technique than that required to land smaller aircraft. One of the pilots said he used a "learned" or "precognitive" attitude time history as reference for attitude control. This consisted of maintaining attitude constant until a certain wheel height and then to make a specific noseup change of attitude, independent of sink rate

or altitude, which he had learned would result in a good flare and acceptable sink rate at touchdown. He depended on the ground effect to provide a significant amount of the lift required to arrest the sink rate. He claims this technique is more open loop in terms of use of h and $\dot{h}$ cues than the technique used to land smaller aircraft. With the control technique used, which is characteristic of very large aircraft, the pilot is more tolerant of, or less sensitive to, time delays inserted in the command path. This is discussed further in Section 4.5. The Short Aft Tail design with α-augmentation was rated poorly even with the low level of time delay. The effect of increasing the time delay was not evident for these configurations.

Part of the reason for the increased tolerance to control system lag and delay that was exhibited in this experiment when the pilot was located large distances ahead of the center of rotation is thought to be attributable to the fact that the pitch acceleration response, although delayed, is amplified and "displayed" to the pilot as normal acceleration. The amplified initial normal acceleration response is easily perceived by the pilot and provides the needed confirmation cue that the airplane is responding to the pilot's control action.

For the $X_{PCR} = -10$ ft Short Aft Tail configurations, there are many points in the Level 2 region which have pilot ratings worse than 6.5 even for the minimum time delay. Again, it appears that the pilot position aft of the center of rotation causes this. There were pilot comments describing delayed response and altitude control problems in flare when there was no extra lags added. The Short Aft Tail configurations for which extra lags and delays were inserted in the command path received pilot ratings of 9 and 10 and PIO ratings of 4, 5, and 6. These latter configurations were similar to $X_{PCR} = +10$ and +50 configurations (except for the changes to move the pilot position with respect to the center of rotation) which received pilot ratings of 4.5 and 5 and PIO ratings of 1 from Pilot A.

Pilot ratings versus level of augmentation are presented in Figures 23 and 24 for α and q augmentation, respectively. There is a slight trend

towards better ratings as the α augmentation level is increased. The trend to better ratings is much more pronounced with the q augmented configurations. With the α augmented configurations, as the feedback was increased, the short period frequency increased to high values making the configuration stable and then increasingly quicker and responsive. However, along with the higher level of static stability came some non-beneficial characteristics. Large forces were required to hold speeds off of trim and to keep the aircraft level in turns where large angle of attack changes were necessary. In addition, as the stability increased, so did the turbulence response as discussed in Section 4.6. The pilots commented that these higher augmented configurations had better initial response characteristics but did not seem to hold attitude and predictability of final attitude was not as good as desired. Attitude, airspeed and flight path control required high workload in turbulence.

The α-augmented airplanes tended to hold α and, in turbulence and ground effect, there was considerable low frequency variation of attitude and airspeed which required increased pilot attention and workload to control. The airplanes were repeatedly described as ponderous in the IFR approach and difficult to control during flare and touchdown. The phugoid mode becomes more noticeable and is likely the cause of these observations and the pilot ratings of the α configurations.

The q-augmented configurations generally had better pilot ratings and comments than the α-feedback configurations as the level of augmentation increased. [An exception is the Pilot A evaluation of the High q-configuration performed on 8/4/80. (See Pilot Comments on page III-15.) This evaluation was performed with a tailwind and may have been influenced by wind shear.] The primary reason for this is the attitude-hold feature for these q-feedback configurations. This made precise control of pitch attitude much easier near touchdown because the control system rejected pitch disturbances due to ground effect. The pilots could make a small input and know where the final attitude would be. This was especially helpful with the X_{PCR} = -10 ft Short Aft Tail configuration which did not provide the necessary motion cues to tell the pilot he had made the proper corrections. He could learn to fly with an open-loop technique making small

occasional pulse-like inputs to correct flight path errors. The pilots were favorably impressed with the level turn feature without pitch inputs in the q-augmented configurations. This completely eliminated the fatigue resulting from turning maneuvers with the higher α-augmented configurations. Turbulence response, which is discussed in Section 4.6, was also much less with these q-feedback configurations due to the low static stability of the basic airplane and the tendency of the control system to hold attitude and zero pitch rate. When the pitch rate augmented airplanes were "trimmed" and the pilot had the right thrust setting, they tended to hold airspeed very well, even in turbulence.

4.2.2 Lateral-Directional Results

Generally, the lateral-directional characteristics were not a factor in the evaluations. Turns were automatically coordinated, so sideslip and the Dutch roll mode were not excited with roll inputs. There were some complaints due to the low Dutch roll frequency (.5 rad/sec) which made the pilots call the configuration "ponderous" when they had to use yaw control as in the sidestep maneuver, and crosswind and turbulence corrections.

4.3 PITCH ATTITUDE PILOT/AIRCRAFT CONTROL LOOP ANALYSIS

4.3.1 Introduction

Analysis of the pitch-attitude pilot/aircraft control loop was performed on the evaluated configurations. These included open-loop analysis of the aircraft alone without pilot: θ/F_{ES}, open-loop analysis of aircraft plus pilot without any pilot compensation: $\theta/\theta_{\varepsilon}$ (no compensation), and closed-loop analysis of entire pitch attitude control system with pilot compensation. The pitch attitude control loop structure is shown in Figure 26. Results from the open-loop aircraft configuration and uncompensated pilot analysis is presented in Appendix V-C and V-D. The closed-loop analysis is presented here.

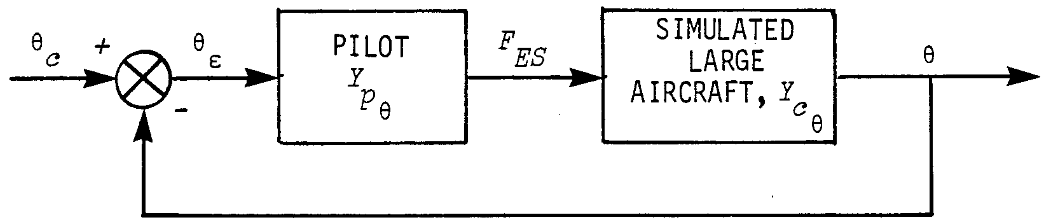


Figure 26. PITCH ATTITUDE CONTROL LOOP STRUCTURE

The analysis is derived from the work by Neal and Smith reported in Reference 5. The basic approach is to model the pilot-airplane pitch attitude control loop as a unity feedback system with a pilot model of an assumed form in the forward loop. The form of the assumed pilot model permits accounting for the following characteristics exhibited by pilots when controlling dynamic systems:

- Adjustable gain.
- Time delay.
- Ability to develop lead or to operate on derivative or rate information.
- Ability to develop lag or to "smooth" inputs. (Lag was not used on the configurations investigated because of their low frequency characteristics).
- Ability to provide low frequency integration.

The form of the pilot model defined below accounts for the observed capabilities and limitations of the pilot with sufficient accuracy to permit approximate analysis of the dynamics of the closed-loop, pilot-airplane system in pitch. It should be emphasized that it is not necessary for the pilot model to be an exact analog of the human pilot for it to be useful in the context of a design criteria. The design criteria is based on the hypothesis that if good closed-loop dynamic performance can be achieved with an autopilot of the form

described by the assumed pilot model, then the human pilot will also be able to achieve good closed-loop dynamic performance.

The pilot model used is:

$$Y_{P_\theta} = K_{P_\theta} e^{-.25s} \left(\frac{5s+1}{s}\right)(\tau_L s+1)$$

The gain, K_{P_θ}, is in the units of pounds/rad.

The $e^{-.25s}$ term accounts for time delay in the pilot's neuromuscular system. The value of 0.25 sec. is based on delays observed in records for the discrete tracking task performed in References 5 and 6. These records exhibit delays ranging from 0.20 to 0.40 seconds. The value of 0.25 was selected on the basis of cut and try data correlation and is interrelated with the bandwidth frequency that is specified for a given flight phase or task.

The $\frac{5s+1}{s}$ term provides low frequency integration capability. A form of the pilot model without this term can be used when constant speed or two degree-of-freedom equations are used to represent the airplane. In that case, the airplane transfer function should have a free s in the denominator and low frequency integration by the pilot will not be necessary. When three degree-of-freedom equations are used, as is the case in the present analysis, or when the flight control system uses high gain attitude stabilization, it may be necessary for the pilot model to perform low frequency integration to avoid droop at frequencies less than ω_{BW}.

The $(\tau_L s+1)$ term accounts for the lead that the pilot provides to achieve desired closed-loop performance and is a measure of his workload.

Because the closed-loop,pilot-airplane dynamic system has been modeled as a negative feedback system with unity gain in the feedback path, it

is possible to relate the dynamic characteristics of the elements in the forward loop, $\theta/\theta_\varepsilon = Y_{p_\theta} Y_{c_\theta}$, to the dynamic characteristics of the closed-loop system, $\theta/\theta_c = \frac{Y_{p_\theta} Y_{c_\theta}}{1+Y_{p_\theta} Y_{c_\theta}}$, through use of a Nichols diagram, (Figure 27). This diagram consists of the superposition of two grid systems. The rectangular grid is the magnitude and phase of the forward loop dynamic elements $Y_{p_\theta} Y_{c_\theta}$ and the curved grid system represents the magnitude and phase of the closed-loop system $\theta/\theta_c = \frac{Y_{p_\theta} Y_{c_\theta}}{1+Y_{p_\theta} Y_{c_\theta}}$. Therefore, one can determine the closed-loop dynamic characteristics by plotting the magnitude and phase data of $Y_{p_\theta} Y_{c_\theta}$ for a range of frequency on the rectangular grid.

It is hypothesized that a given Flight Phase or task performed in a typical environment will require certain minimum dynamic characteristics of the closed-loop,pilot-airplane system. The parameters used to define the closed-loop dynamic performance are bandwidth, droop at frequencies below the band width,and resonance magnitude. These closed-loop system parameters are defined by the curved lines on Figure 27. The maximum droop permitted for $\omega < \omega_{BW}$ is -3.0 db. This value has been defined somewhat arbitrarily but can be justified from examination of discrete tracking task records in References 5 and 6 and by interpretation of pilot comments in these references.

The closed-loop system resonance limits for Level 1 and Level 2 have been determined from empirical data correlation.

The bandwidth frequency is dependent upon the task.

In application of this design criteria, the designer must succeed in finding a combination of K_{p_θ} and τ_L which will cause the amplitude and phase data for $Y_{p_\theta} Y_{c_\theta}$ to plot in the Level 1 or Level 2 regions of Figure 27. It is necessary, therefore, to perform a parameter search. This search procedure is not difficult and can be performed graphically using graphical aids described in Reference 5 or the process can be mechanized on a digital computer.

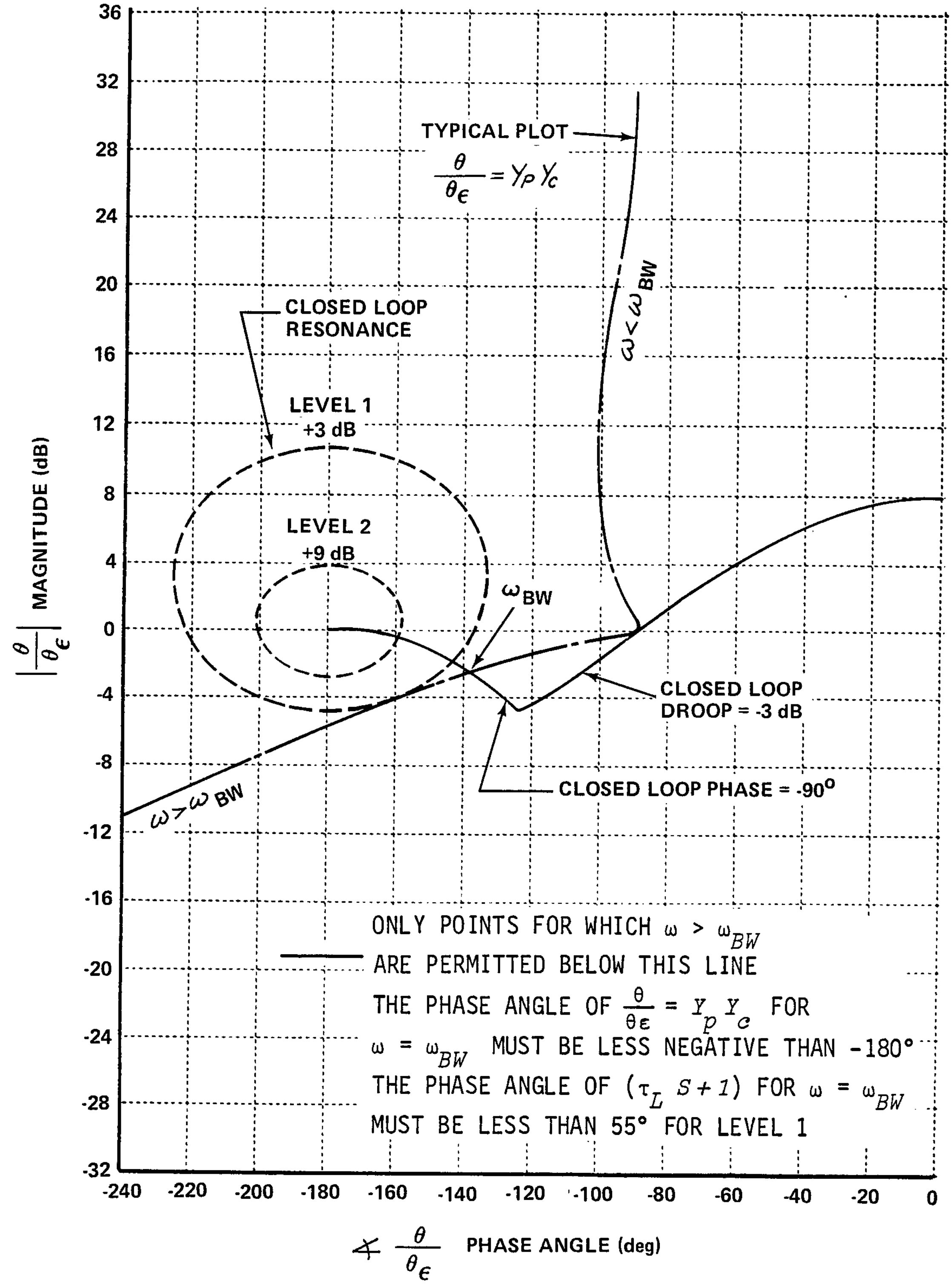


Figure 27. DESIGN CRITERIA FOR PITCH DYNAMICS WITH THE PILOT IN THE LOOP

Because the calculations involved in evaluating the magnitude and phase of $Y_p Y_c$ as a function of frequency are simple to perform, it is feasible to use a simple trial and error approach to test whether or not a proposed airplane design meets the design criteria for closed-loop performance.

4.3.2 Pilot Compensation (Neal-Smith) Analysis

In this analysis, pilot lead compensation ($\tau_L s+1$) was obtained that would make the open-loop compensated pilot plus aircraft transfer function ($\theta/\theta_\varepsilon$) drawn on a Nichols diagram pass through the acceptable closed-loop criteria region (see Figure 27). That is, provide the appropriate gain and lead to keep closed-loop resonance less than +3 dB and closed-loop droop less than -3 dB for $\omega < \omega_{BW_\theta}$. The bandwidth frequency is defined as the frequency which results in a closed-loop phase of -90 degrees. The bandwidth chosen for this set of data was 1.5 rad/sec. This value appears appropriate for the relatively low gain task of landing a very large transport which does not require high agility of the closed-loop pilot-airplane system. In addition, this value of bandwidth resulted in pilot lead compensation that correlated well with pilot ratings.

To obtain the pilot compensation, lead was added to force the 1.5 rad/sec point through the -90 deg. closed-loop phase line with the $\theta/\theta_\varepsilon$ plot just skimming the +3 dB closed-loop resonance boundary. The resulting closed-loop droop was much less than -3 dB (near 0 dB) for most configurations. Lower resonance could have been obtained with the droop still not dropping below -3 dB if more lead compensation was used. The solutions chosen, therefore, represent minimum pilot lead required to meet the performance standard. The maximum lead time constant used was approximately 7 seconds. This results in lead of: $\tan^{-1}(\tau_L \omega_{BW_\theta}) = 85$ degrees at the 1.5 rad/sec bandwidth. This limit is arbitrary but represents the situation of diminishing returns that occurs in the closed-loop system, i.e., extreme increases in pilot lead do little to improve closed-loop performance. For a few cases, the performance criterion of less than 3 dB resonance could not be achieved with this maximum lead.

The aircraft (with the 25 rad/sec feel system) plus compensated-pilot open-loop $\theta/\theta_\varepsilon$ transfer functions for each configuration evaluated are presented in Appendix IV. The lead time constant in seconds, phase compensation at the bandwidth ($\measuredangle PC = tan^{-1}\ 1.5\ \tau_L$), and pilot gain are presented in Table VIII. Plots of pilot ratings versus the pilot compensation, $\measuredangle_{PC}$, are presented in Figure 28. All of Pilot B's ratings are included although many were performed using the 15 rad/sec feel system.

From the results of the overall experiment, there is a definite trend towards worse pilot ratings as more pilot compensation is required. From the Long Aft Tail and Canard configurations data, it appears that the phase compensation must be less than 55 degrees for Level 1 ratings and less than 75 degrees for Level 2 ratings. The points with large pilot compensation correspond to the configurations with low augmentation levels and extra time delays and lags added. The correlation of pilot rating and pilot compensation generally agrees with data from Reference 5 and 9. This means that the amount of phase compensation at the bandwidth frequency required to meet the closed-loop performance criteria is a good measure of pilot acceptance of the configuration. The same values appear to be valid for fighter tasks as well as transport approach tasks as long as the appropriate bandwidth is chosen.

The Short Aft Tail configurations do not appear to correlate well with this criteria. Pilot ratings up to 10 were received for configurations which required only 55 degrees of phase compensation. The Extra-High q-augmented configuration required only 17 degrees of compensation but received a pilot rating of 4. This again points out the fact that the pilot uses more than just pitch attitude in his control scheme. Normal acceleration, altitude rate, and altitude responses at the pilot position must also be important.

The q-augmented configurations consistently received better ratings than the α-augmented ones even though the required pilot compensation was nearly the same. This again shows that characteristics other than closed-loop attitude control are affecting pilot ratings. The attitude hold and no pitch force in turns features of the q-augmented configurations definitely

TABLE VIII. PILOT COMPENSATION FOR CLOSED-LOOP θ/θ_c BANDWIDTH

ω_{BW}=1.5 rad/sec (90^{o} Closed Loop Phase Lag)

$$Y_{P_\theta} = K_{P_\theta} e^{-.25s} \left(\frac{5s+1}{s}\right)(\tau_L + 1)$$

Configuration	LEVEL OF DELAY (T_1)								
	A			B			C		
	τ_L *sec*	*Lead @* ω_{BW} $\measuredangle$ *PC** *deg*	K_{P_θ} *lb/rad*	τ_L *sec*	*Lead @* ω_{BW} $\measuredangle$ *PC** *deg*	K_{P_θ} *lb/rad*	τ_L *sec*	*Lead @* ω_{BW} $\measuredangle$ *PC** *deg*	K_{P_θ} *lb/rad*
Short Aft									
Med α	1.13	59	1.61	1.60	67	1.26			
High α	.93	54	1.77	1.33	63	1.40			
Med q	4.67	82	.73						
High q	.97	55	1.32				(3.67	80	.44)**
Ex-High q	.21	17	1.26						

* $\measuredangle PC = \tan^{-1} 1.5\, \tau_L$

**T_1 = .35 (shuttle lag/delay)

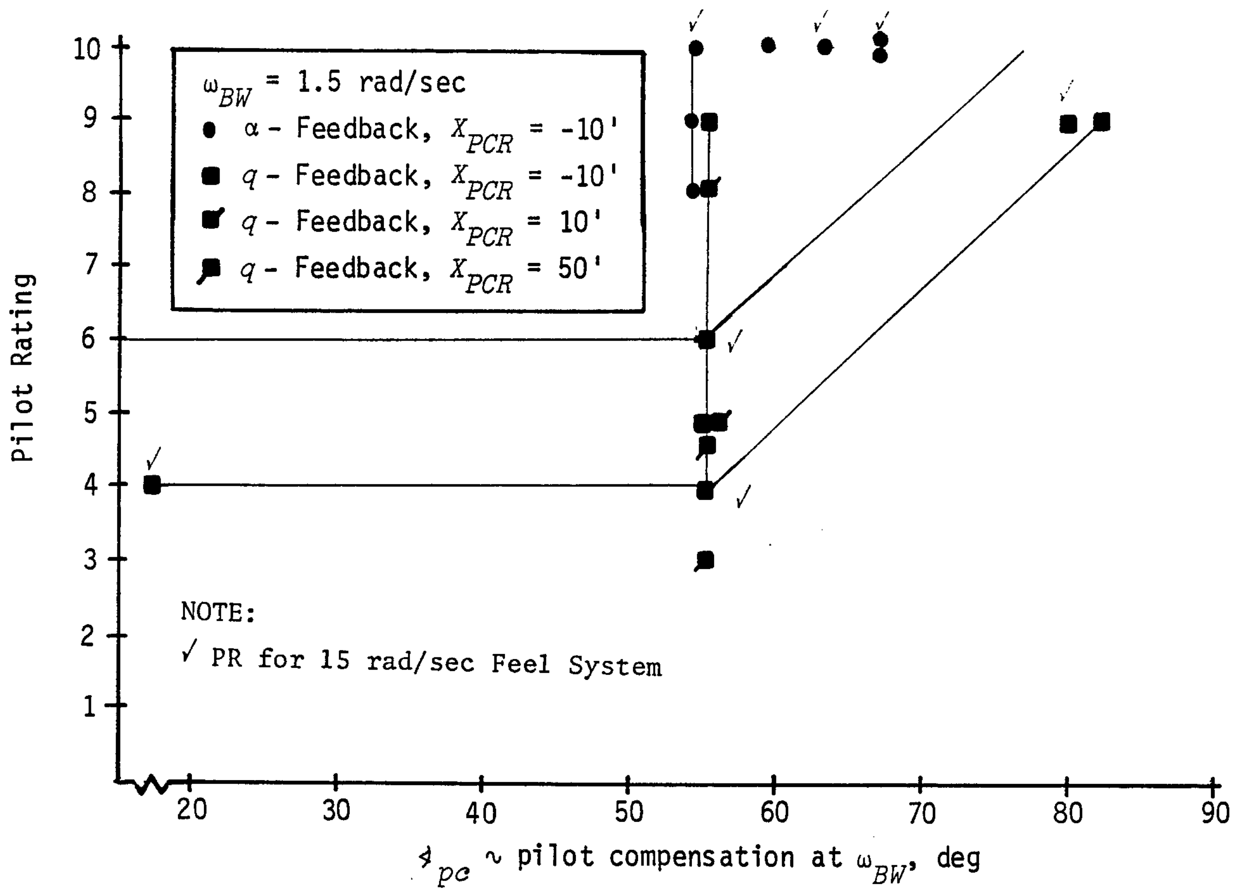


Figure 28. SHORT AFT TAIL PILOT RATINGS VS PILOT LEAD COMPENSATION

improved these ratings over the comparable α-augmented configurations. The q-augmentation significantly reduced the pitch response to turbulence and ground effect-induced pitching moments. The operation of the aircraft on the backside of the power-required curve in conjunction with the slow thrust response also appears to put a limit on the best pilot ratings. The pilots downgraded otherwise good configurations due to the speed control problems.

4.4 EFFECT OF BANDWIDTH ON ALLOWABLE TIME DELAY

From previous experiments dealing with higher order systems and their effective time delays, there appears to be a general increase in the level of time delay acceptable as the task presented the pilot becomes less difficult. Reference 4 compiles much of this data and, in particular, shows the effect of time delay on pilot ratings for three degrees of task difficulty. Data from Reference 5 was obtained from air-to-air combat evaluations. Data from Reference 6 was obtained from fighter landing approach and actual touchdown evaluations. Data from reference 10 was obtained from fighter up-and-away and low altitude waveoff approach evaluations. The closed-loop pitch attitude bandwidth which the pilots were generally believed to be requiring in these experiments were 3.5 rad/sec, 2.5 rad/sec , and 1.5 rad/sec, respectively as the task became less critical and the pilot did not have to be as aggressive. Shown in Figure 29 are the bands of effective time delay t_1, calculated from the maximum slope intercept method, associated with the boundaries of flying qualities levels (pilot rating of 10, 6.5, 3.5) versus the bandwidth for the evaluation task. The data from which these bands were obtained are from configurations that were rated Level 1 with minimal time delay. It can easily be seen that the pilot becomes much more tolerant of, or less sensitive to, time delays as the tasks become less critical. The landing approach and simulated touchdown task of the present experiment with a large, slow responding aircraft can be considered as having the same bandwidth requirements (1.5 rad/sec) as the fighter up-and-away and low altitude waveoff task of Reference 10. The data from the present experiment tends to verify the trend shown — large time delays become acceptable at low bandwidth and relatively little degradation in pilot rating results from the large variation of time delay. (This observation is derived mostly from data documented in the Air Force report on the overall experiment).

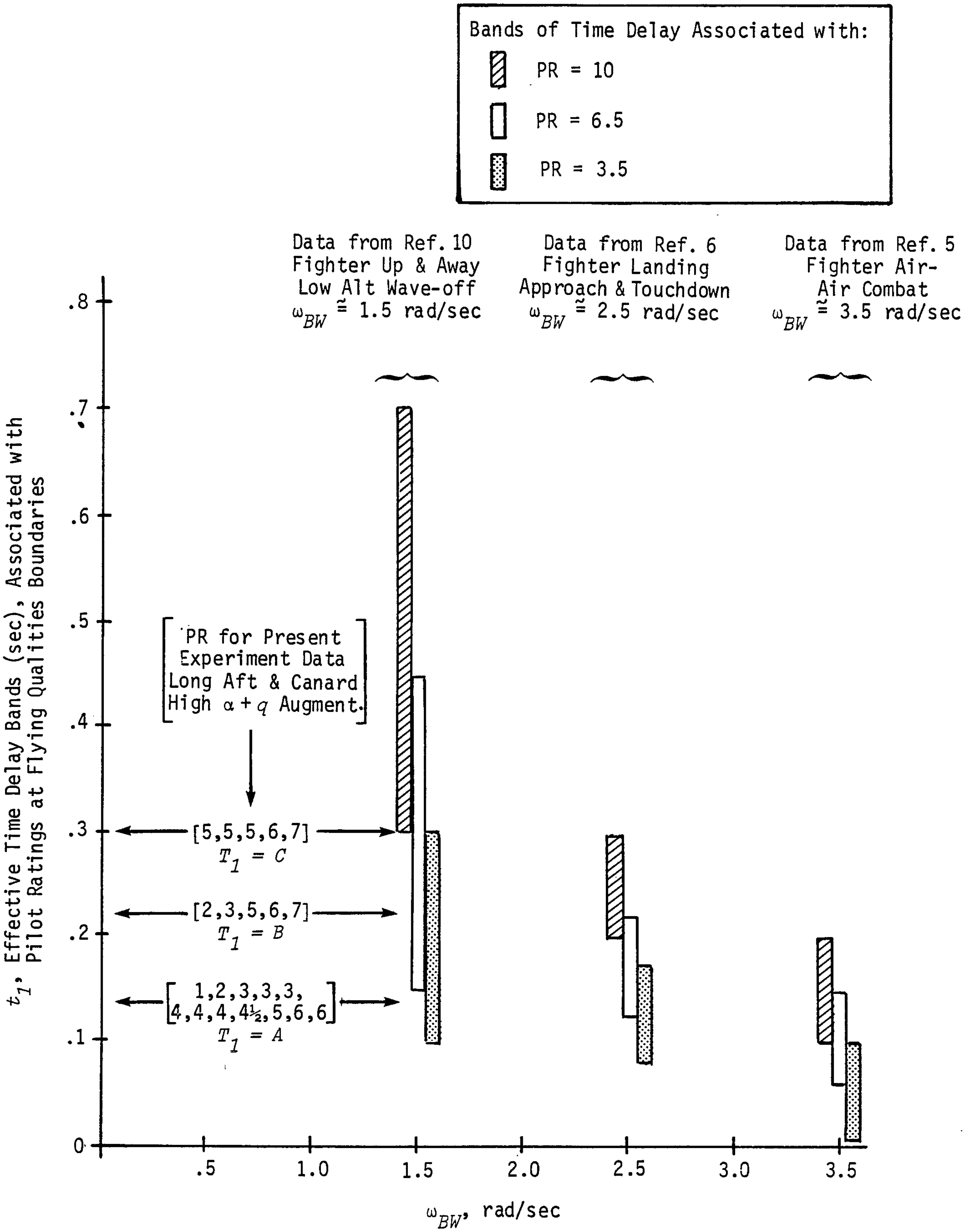


Figure 29. TIME DELAY BANDS ASSOCIATED WITH FLYING QUALITIES BOUNDARIES VS BANDWIDTH

A functional relationship was determined between the average tolerable effective time delay and bandwidth for the task for pilot ratings of 10, 6.5, and 3.5. These are the boundaries for Level 3,2, and 1 flying qualities. In the relationships derived, the allowable effective time delay, t_1, was inversely proportional to the bandwidth of the task for the various flying qualities levels:

$$@\ PR = 10 \qquad t_1 = \frac{.65}{\omega_{BW}}$$

$$@\ PR = 6.5 \qquad t_1 = \frac{.4}{\omega_{BW}}$$

$$@\ PR = 3.5 \qquad t_1 = \frac{.3}{\omega_{BW}}$$

These relationships are plotted on Figure 30, along with the data from the Long Aft Tail and Canard, High α and q-augmented configurations. For the data from the present experiment, the average pilot ratings increased from approximately 3.5 to 6 as the effective time delay increased from .14 to .3. This tends to support the relationships shown at ω_{BW} = 1.5 rad/sec.

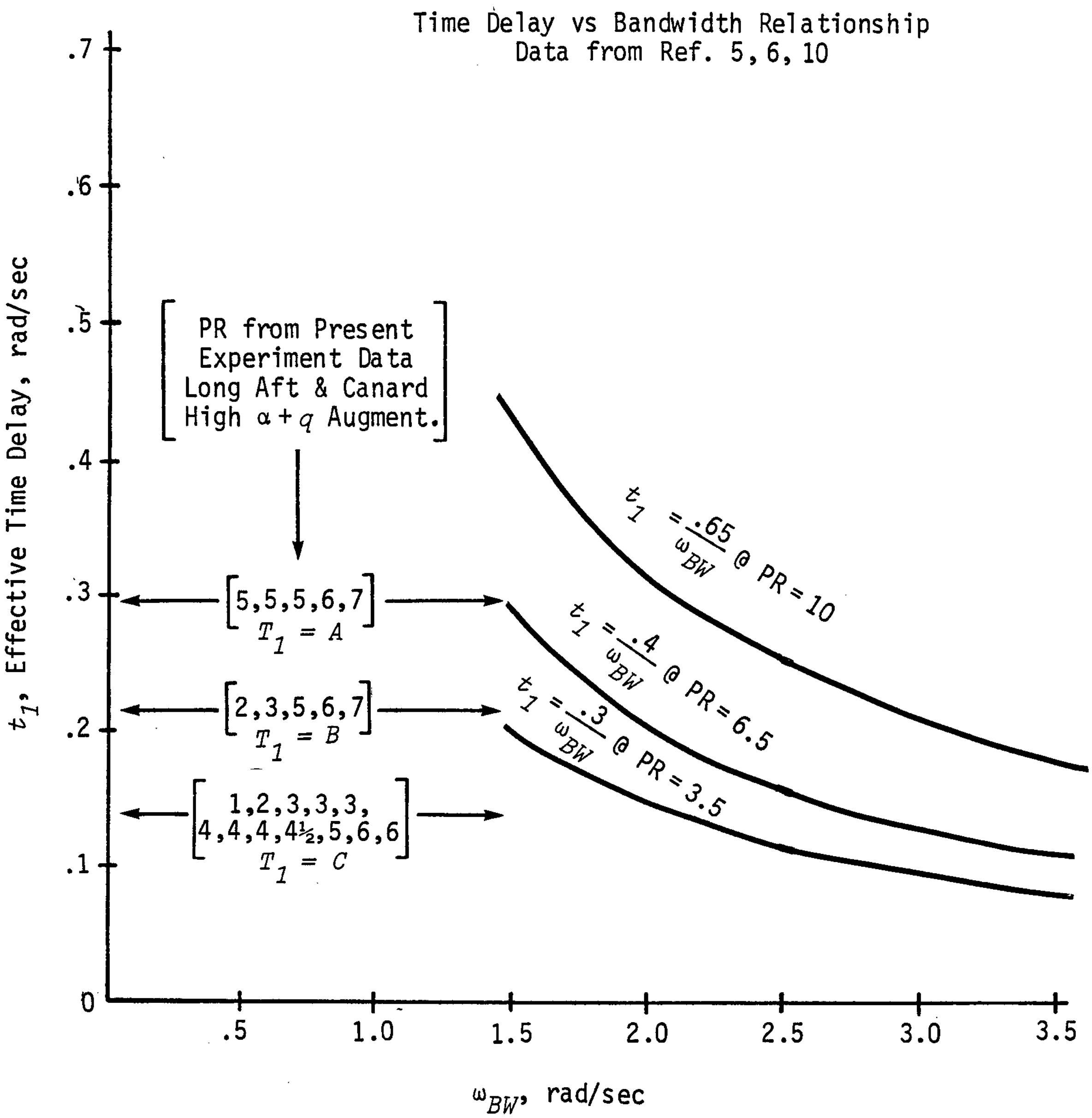
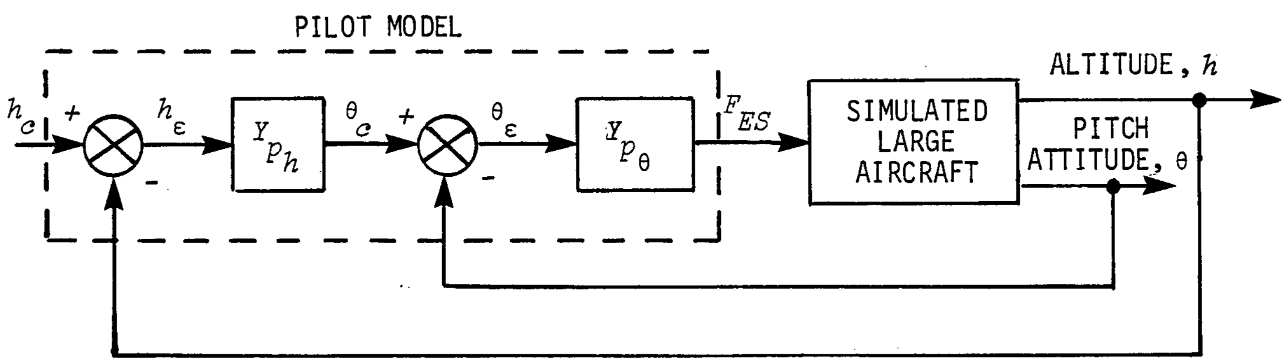


Figure 30. TIME DELAY VS BANDWIDTH @ PR = 10, 6.5, 3.5

4.5 MULTI-LOOP ANALYSIS

In order to better understand the evaluations of configurations with varying pilot position versus instantaneous pitch center of rotation with all other characteristics constant, a multi-loop analysis was performed. The model of the control structure is shown in Figure 31. There is an inner pitch attitude control loop with an outer altitude control loop in series. In the outer loop, the pilot is controlling the altitude he sees at the pilot station. The inner loop pilot gain (K_{P_θ}) and lead (τ_L) were fixed at the values obtained in the pitch attitude closed-loop analysis (Section 4.3.2) where a bandwidth of 1.5 rad/sec was achieved. The pilot model for the outer loop was a pure gain, K_{p_h}, regulating the perceived altitude error, h_ε, at the pilot's position. The lead term in the inner loop ($\tau_L s+1$) effectively gives some lead in the altitude loop also.



$$Y_{p_\theta} = K_{p_\theta} e^{-.25s}\left(\frac{5s+1}{s}\right)(\tau_L s + 1), \text{ pound/rad}$$

$$Y_{p_h} = K_{p_h}, \text{ rad/ft}$$

Figure 31. CONTROL STRUCTURE FOR MULTI-LOOP ANALYSIS

Configurations analyzed included the Short Aft Tail, High q-augmented, delay $T_1 = A$, with pilot position X_{MP} = 50, 70, 110 feet or pilot position with respect to the center of rotation (X_{PCR}) of 10 feet aft, 10 feet forward, and 50 feet forward, respectively. In addition, the Short Aft Tail, High q-augmented configuration with extra delay, T_1 = .35 (equivalent to the shuttle's lag/delay) and the Extra-High q-augmented configuration were analyzed.

The analysis is based on the transfer functions in Appendix I which are evaluated at the nominal trim speed. Complete transfer functions were used without simplification or approximation. The time delays were treated in $e^{-\tau s}$ form. The computer program developed in Reference 12 was used to calculate root loci and Nichols diagrams were used to determine closed-loop bandwidth. It should be noted that the Short Aft Tail configurations have a low frequency factor in the numerator of the altitude-elevator transfer function that is in the right half plane as a result of being on the "backside." The analysis performed considered multiple feedback to a single controller, the elevator. This loop closure results in a low frequency pole of the closed-loop system being driven toward the low frequency zero of the altitude-elevator transfer function; this root was unstable.

Configuration	Zero Location	Closed Loop Pole
Short Aft	+.0037	+.0036 for $K_{p_h} = .010$

In order to stabilize this closed-loop pole, it would be necessary to close a low gain feedback loop of airspeed to the throttle. This loop closure was not included in the analysis and the results described in the following paragraphs must be viewed with that fact in mind.

Although the closed-loop system transfer function was 11th order over 15th order and included time delay, the results of the analysis will be discussed in terms of the dominant set of complex roots of the closed-loop altitude-stick force dynamic system.

The results are presented in two sets of figures and TABLE IX. Figures 32 through 37 show the altitude error mode root locus as a function of the pilot altitude gain, K_{p_h}. Figures 38 through 43 are Nichols plots of the open loop, h/h_ε transfer function, on which the closed-loop 3 dB and 9 dB resonance levels, closed-loop 90° phase lag, and closed-loop 3 dB droop lines are drawn. On these latter plots, the closed-loop criterion curves have been shifted by the appropriate gain to achieve the highest possible altitude closed-loop bandwidth

TABLE IX. RESULTS OF MULTI-LOOP ANALYSIS

Configuration	X_{PCR}, ft Center of Rotation to Pilot	Inner Pitch Loop Pilot Model (Achieves $\omega_{BW_\theta} = 1.5$ rad/sec)	Outer Altitude Loop: Gain, K_{P_h} (rad/ft) for ω_{BW_h}	Outer Altitude Loop: Highest Bandwidth Achievable ω_{BW_h}, rad/sec	Pilot Rating	PIO Rating
Short Aft Tail, High q $X_{MP} = 50'$, $T_1 = A$	-10	$1.32e^{-.25s}(.97s+1) \cdot \left(\frac{5s+1}{s}\right)$	.0016	.43	9,5,6,4	4,3,3,2
Short Aft Tail, High q $X_{MP} = 70'$, $T_1 = A$	10	$1.32e^{-.25s}(.97s+1) \cdot \left(\frac{5s+1}{s}\right)$	.0017	.45	5	1
Short Aft Tail, High q $X_{MP} = 110'$, $T_1 = A$	50	$1.32e^{-.25s}(.97s+1) \cdot \left(\frac{5s+1}{s}\right)$	.0020	.48	4.5,3	1,1
Short Aft Tail, High $X_{MP} = 50'$, $T_1 = .35$	-10	$.44e^{-.25s}(3.67s+1) \cdot \left(\frac{5s+1}{s}\right)$	.0014	.33	9	4
Short Aft Tail, Ex-High q $X_{MP} = 50'$, $T_1 = A$	-10	$1.26e^{-.25s}(.21s+1) \cdot \left(\frac{5s+1}{s}\right)$	.0012	.38	4	2
Short Aft Tail, Ex-High q $X_{MP} = 50'$, $T_1 = A$ includes altitude loop lead	-10	$1.26e^{-.25s}(.21s+1) \cdot \left(\frac{5s+1}{s}\right)$	.0023(.63 +1)	.50	4	2

Inner Loop:

$$Y_{p_\theta} = (1.318)e^{-.25s}(.97\,s + 1)\left(\frac{5s+1}{s}\right)$$

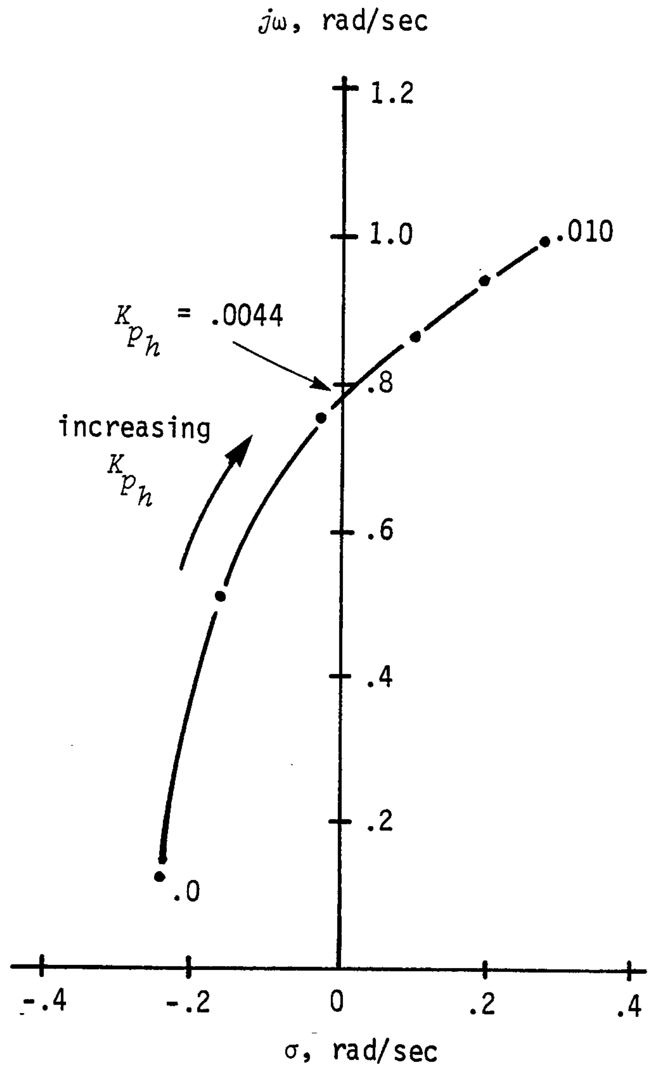


Figure 32. ALTITUDE LOOP ROOT LOCUS VS. K_{p_h} (RAD/FT)
SHORT AFT TAIL, HIGH q FEEDBACK, DELAY = A
X_{MP} = 50', X_{PCR} = -10'

Inner Loop:

$$Y_{p_\theta} = (1.318)e^{-.25s}(.97s+1)\left(\frac{5s+1}{s}\right)$$

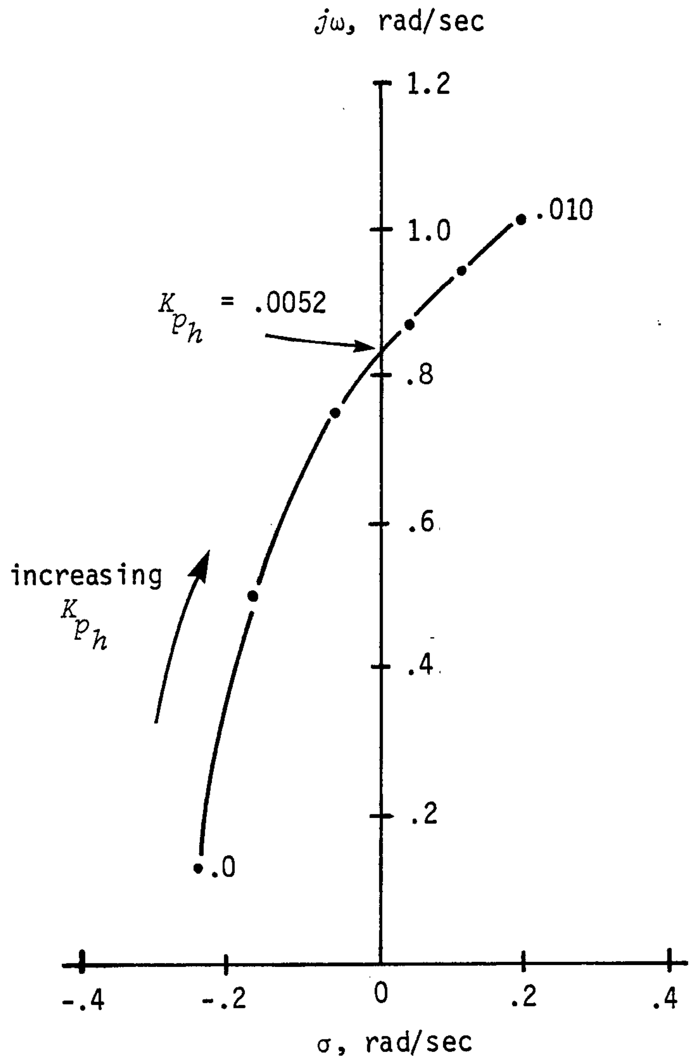


Figure 33. ALTITUDE LOOP ROOT LOCUS VS. K_{p_h} (RAD/FT)
SHORT AFT TAIL, HIGH q FEEDBACK, DELAY = A
X_{MP} = 70', X_{PCR} = 10'

Inner Loop:

$$Y_{p_\theta} = (1.318)e^{-.25s}(.97s+1)\left(\frac{5s+1}{s}\right)$$

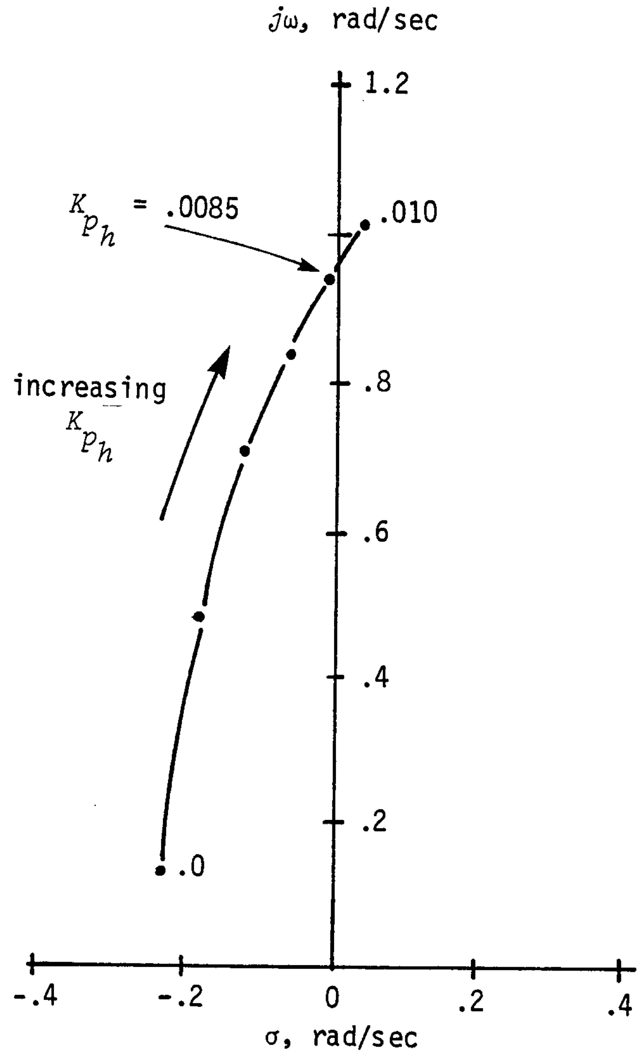


Figure 34. ALTITUDE LOOP ROOT LOCUS VS. K_{p_h} (RAD/FT)
SHORT AFT TAIL, HIGH q FEEDBACK, DELAY = A
X_{MP} = 110', X_{PCR} = 50'

Inner Loop:

$$Y_{p_\theta} = (.435)e^{-.25s}(3.67\,s + 1)\left(\frac{5s+1}{s}\right)$$

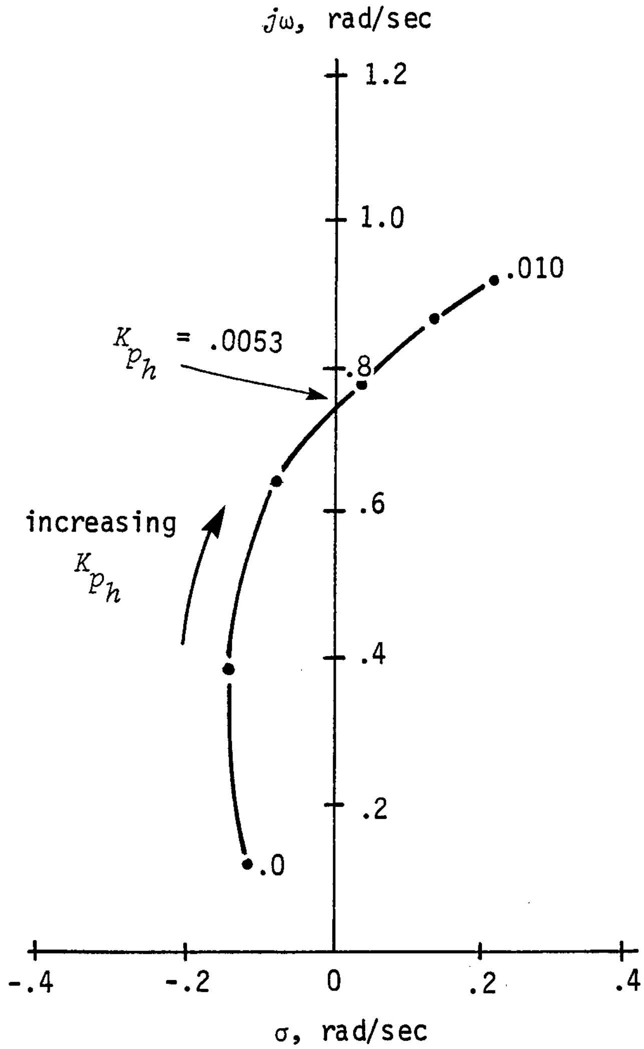


Figure 35. ALTITUDE LOOP ROOT LOCUS VS. K_{p_h} (RAD/FT)
SHORT AFT TAIL, HIGH q FEEDBACK, DELAY = .35
X_{MP} = 50', X_{PCR} = -10'

Inner Loop:

$$Y_{p_\theta} = (1.26)e^{-.25s}(.213\,s + 1)\left(\frac{5s+1}{s}\right)$$

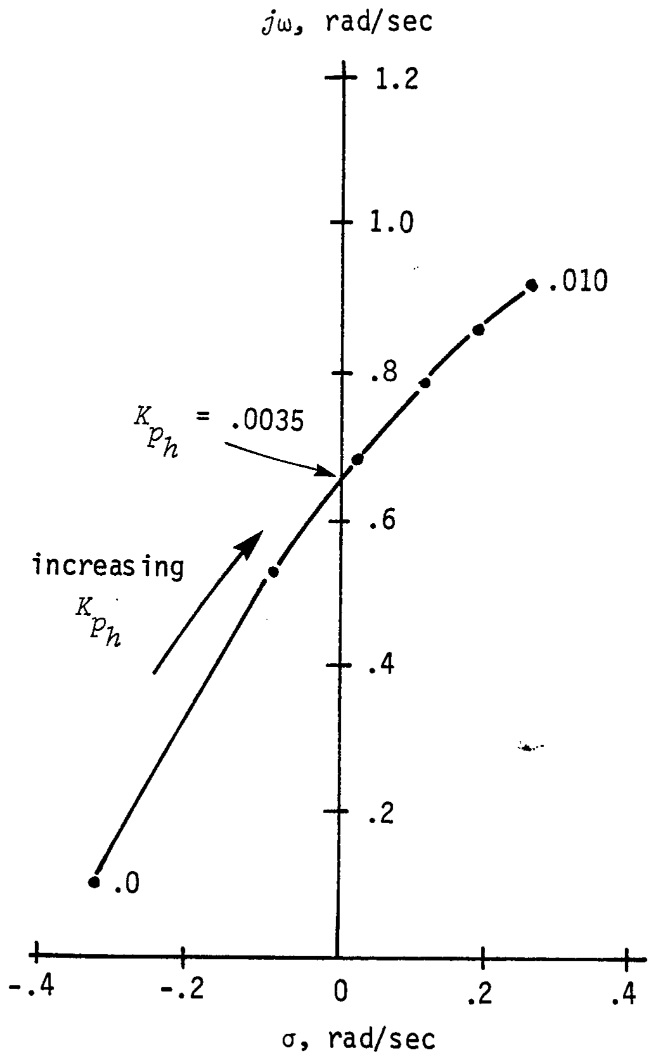


Figure 36. ALTITUDE LOOP ROOT LOCUS VS. K_{p_h} (RAD/FT)
SHORT AFT TAIL, EXTRA-HIGH q FEEDBACK, DELAY = A
X_{MP} = 50', X_{PCR} = -10'

Inner Loop:

$$Y_{p_\theta} = (1.26)e^{-.25s}(.213\,s + 1)\left(\frac{5s+1}{s}\right)$$

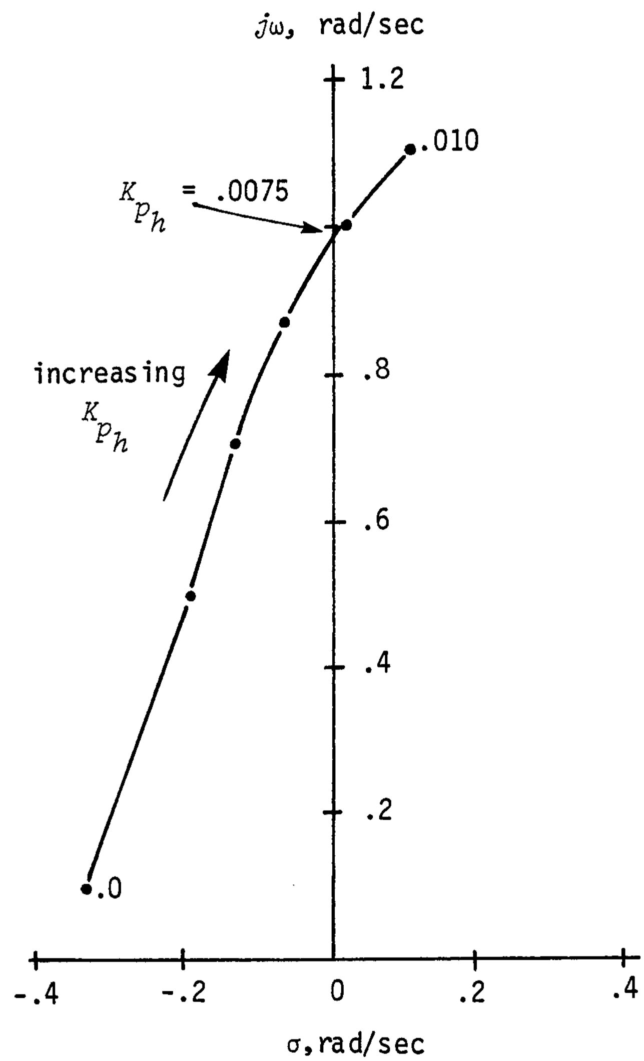
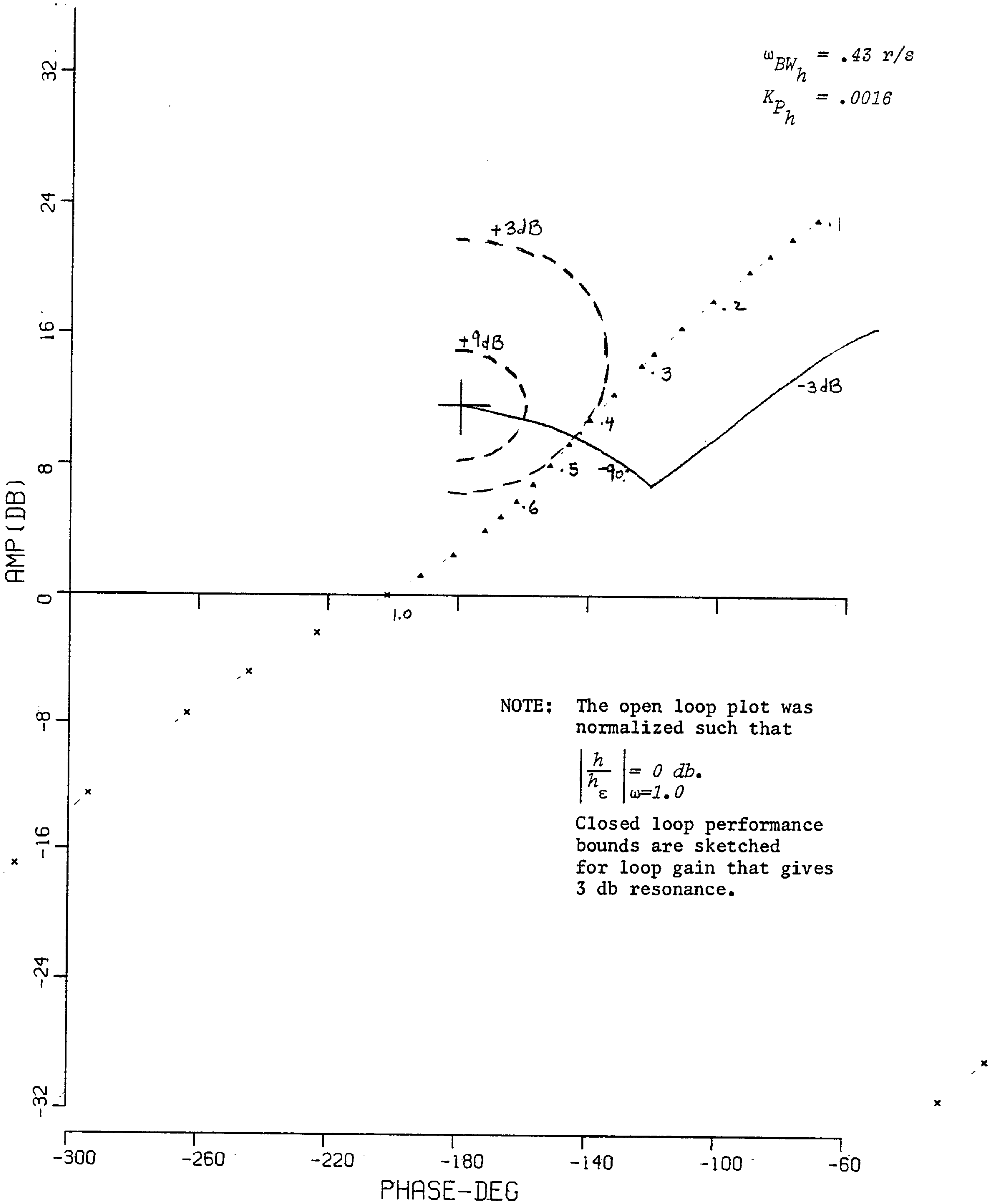


Figure 37. ALTITUDE LOOP ROOT LOCUS VS. K_{p_h} (RAD/FT)
WITH LEAD (.63 s + 1) IN h - COMMAND PATH
SHORT AFT TAIL, EXTRA-HIGH q FEEDBACK, DELAY = A
X_{MP} = 50', X_{PCR} = -10'



NOTE: The open loop plot was normalized such that

$$\left|\frac{h}{h_\varepsilon}\right|_{\omega=1.0} = 0 \text{ db.}$$

Closed loop performance bounds are sketched for loop gain that gives 3 db resonance.

6 MAY 1981 #NWNM1 - S-A TQ=1..KQ=2.5(HI).XP=50 .DEL=A ..MULT-LOOP

Figure 38. SHORT AFT TAIL, HIGH q, X_{MP} = 50', $T_1 = A$, h/h_ε NICHOLS PLOT

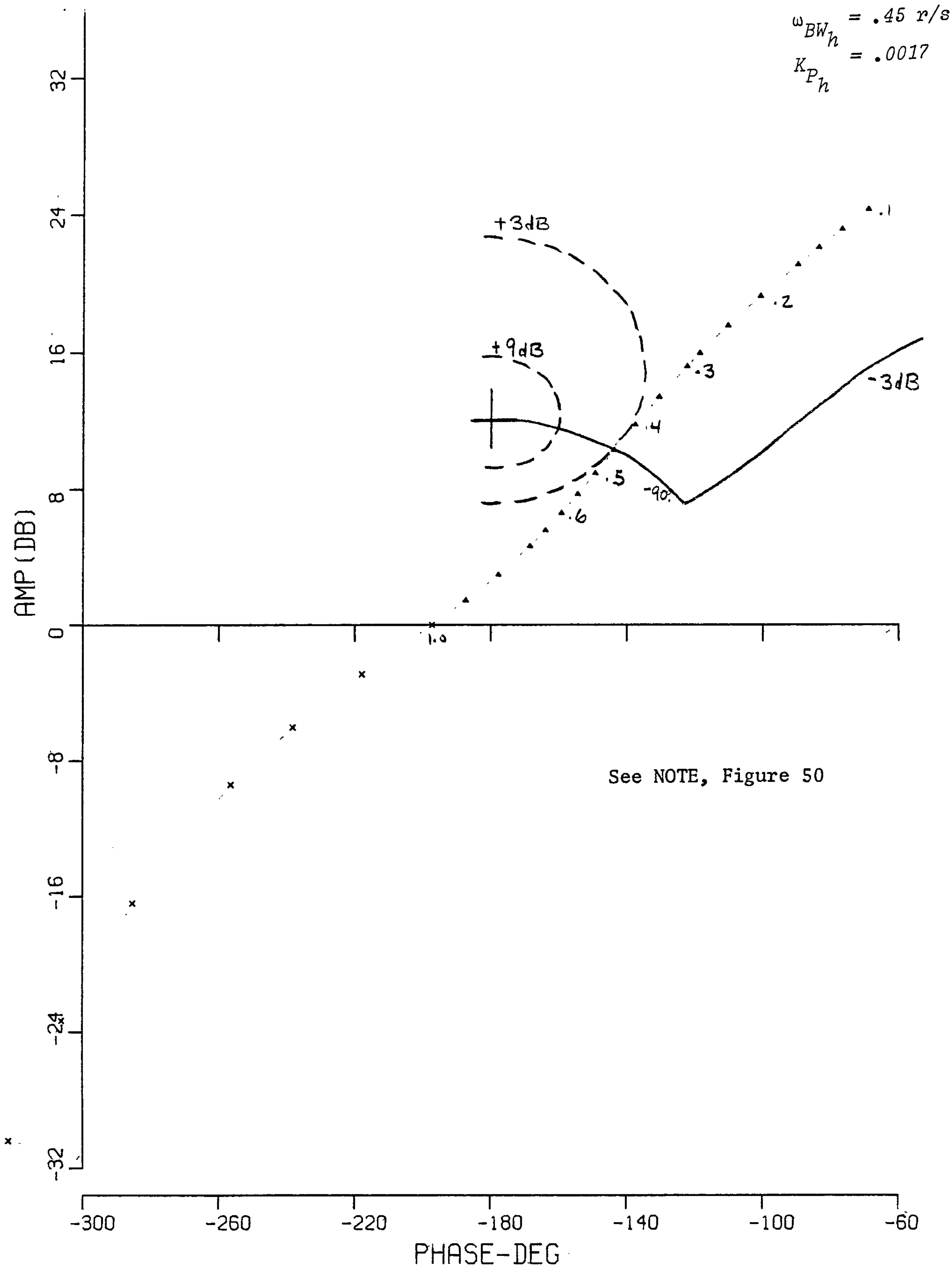
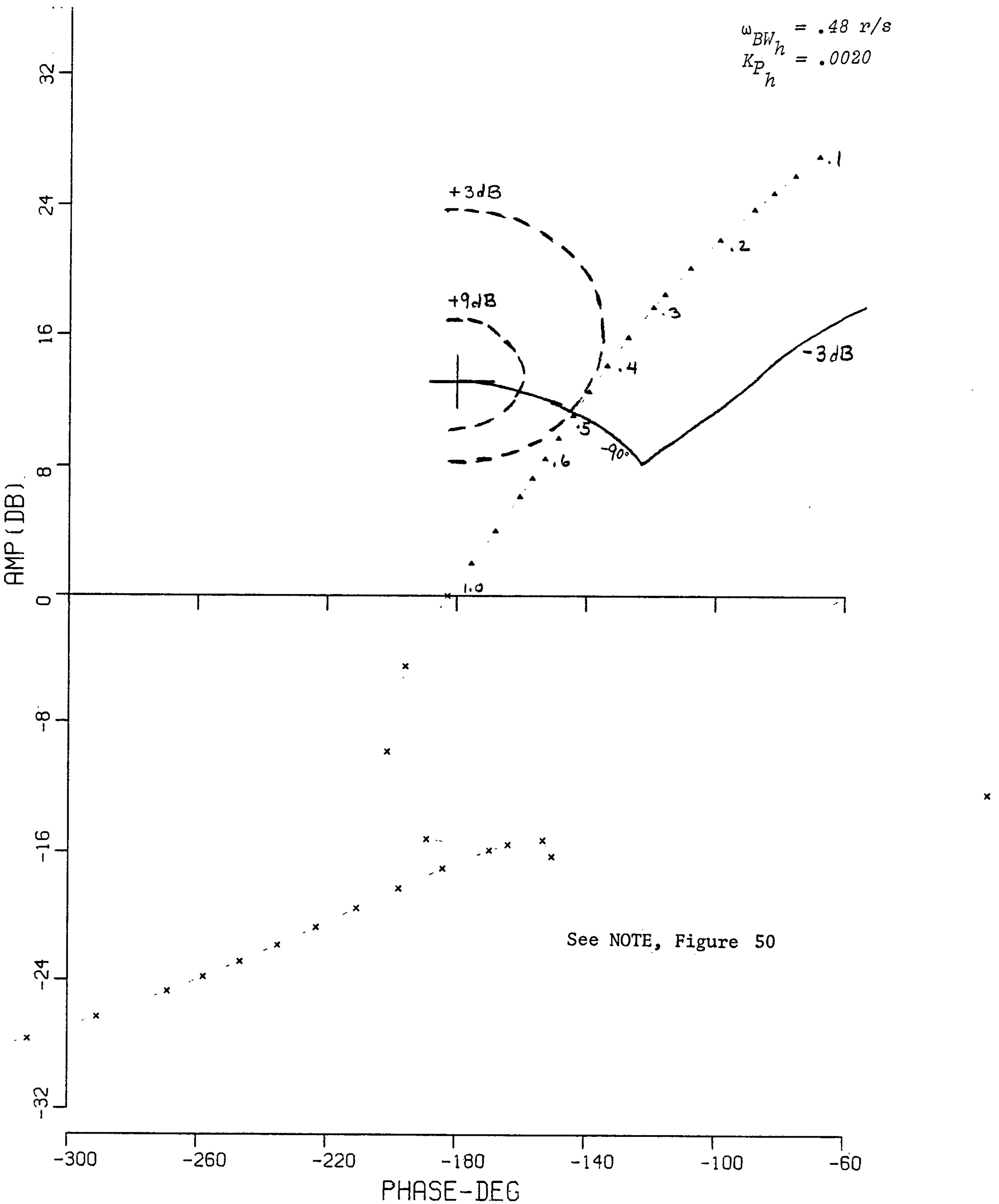


Figure 39. SHORT AFT TAIL, HIGH q, $X_{MP} = 70'$, $T_1 = A$, h/h_ε NICHOLS PLOT



6 MAY 1981 #NWNM3 - S-A TQ=1..KQ=2.5(HI).XP=110.DEL=A _.MULT-LOOP

Figure 40. SHORT AFT TAIL, HIGH q, X_{MP} = 110', $T_1 = A$, h/h_ε NICHOLS PLOT

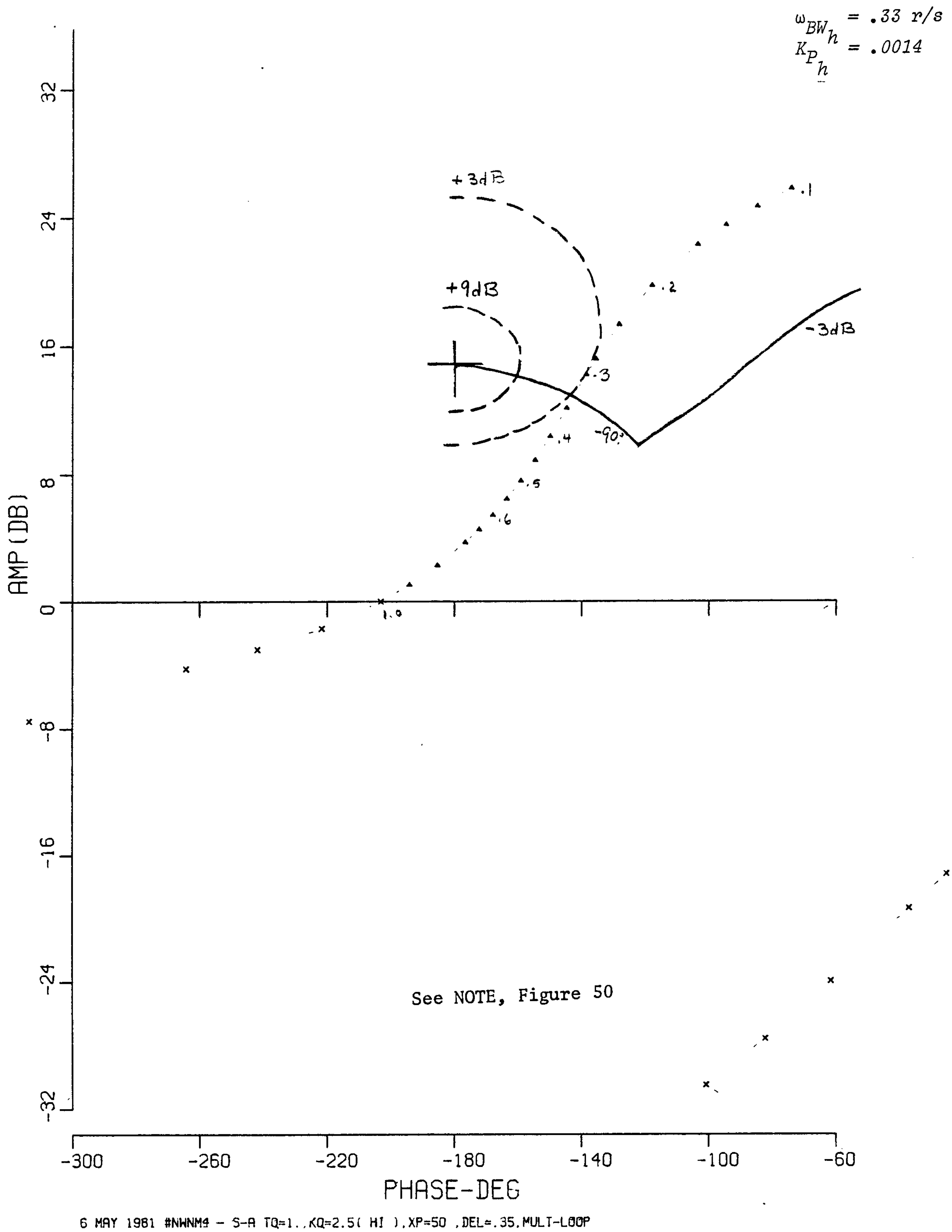
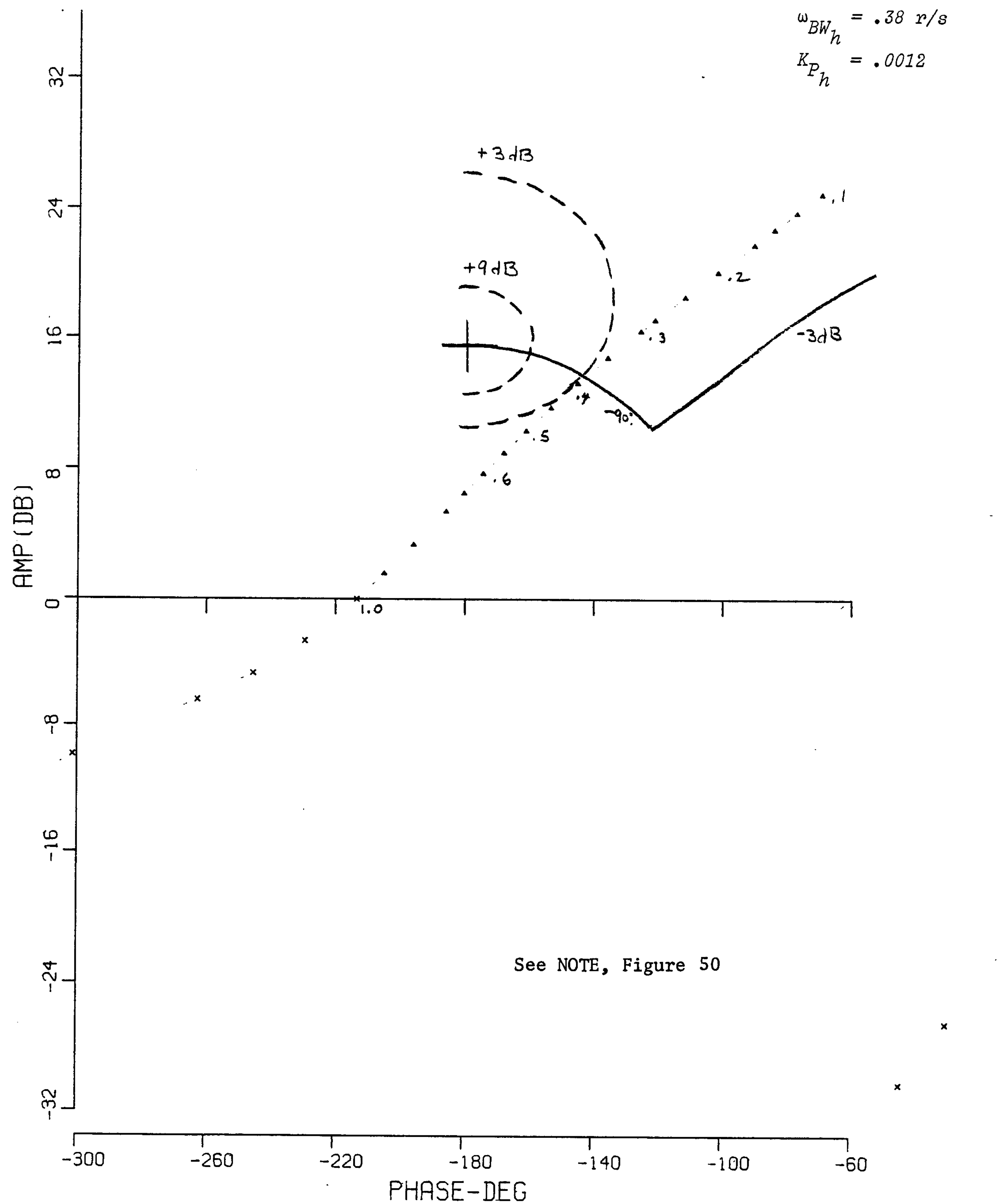


Figure 41. SHORT AFT TAIL, HIGH q, X_{MP} = 50', T_1 = .35, h/h_ε NICHOLS PLOT



6 MAY 1981 #NWNMS - S-A TQ=.5,KQ=5.2(EXHI),XP=50 ,DEL=A ,MULT-LOOP

Figure 42. SHORT AFT TAIL, EX-HIGH q, X_{MP} = 50', $T_1 = A$, h/h_ε NICHOLS PLOT

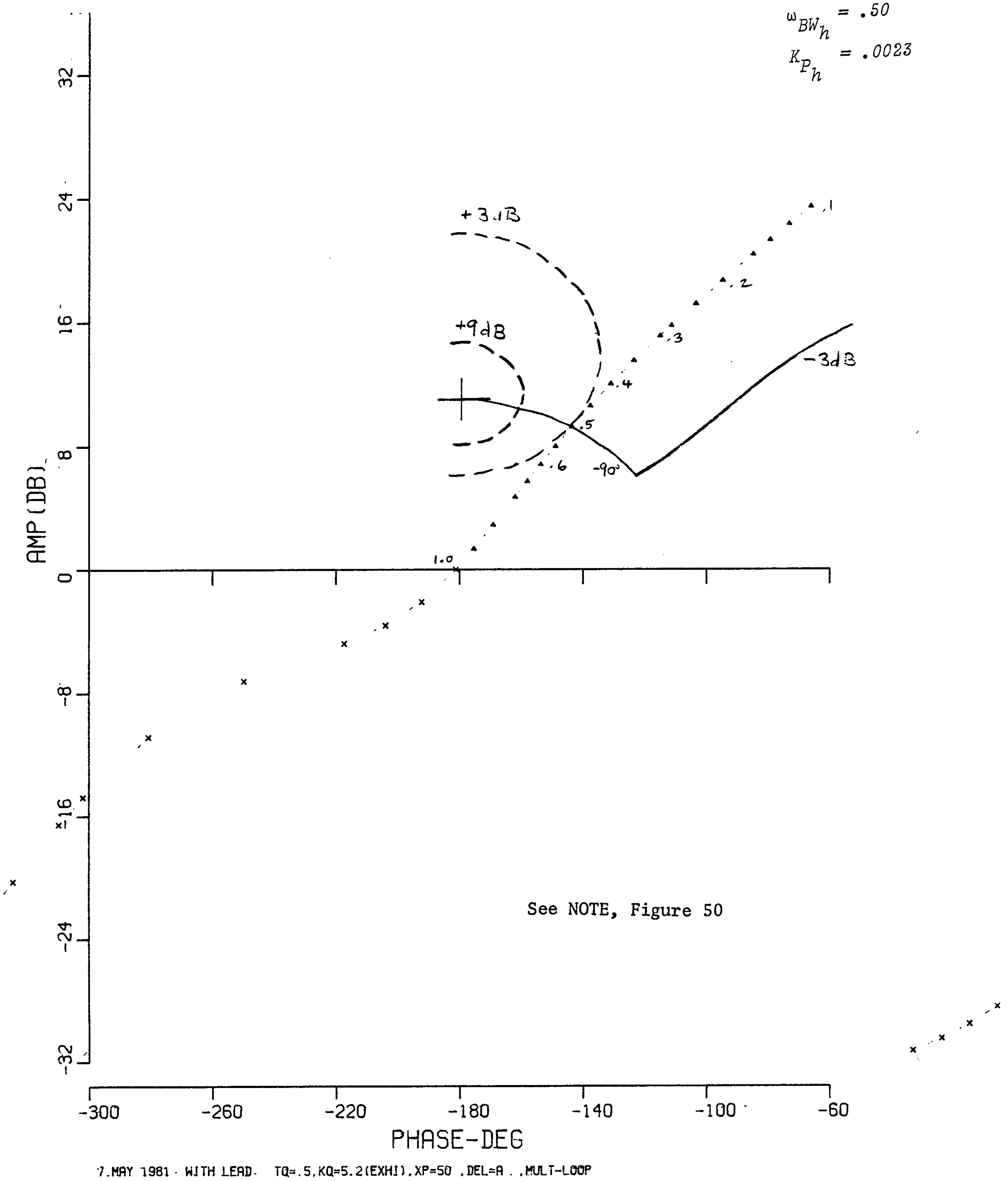


Figure 43. SHORT AFT TAIL, EX-HIGH q, X_{MP} = 50', $T_1 = A$, WITH (.63s+1) LEAD IN ALTITUDE CONTROL, h/h_ε NICHOLS PLOT

(ω at closed-loop 90^{o} phase lag) without violating the 3 dB resonance. This graphical technique was used to illustrate the simplicity of Nichols diagrams for performing dynamic analysis when only the loop gain is being varied.

From the root locus (Figures 32 through 34) for the Short Aft Tail configurations, it can be seen that the altitude mode goes unstable at increasingly higher gain and higher frequency as the pilot position is moved forward. The potential closed-loop bandwidth is thus higher at the more forward pilot locations. Low altitude loop bandwidth correlates highly with the occurrence of PIO's near touchdown. For a given value of K_{p_h} gain, the frequency of the closed-loop root increases as the pilot distance ahead of the center of rotation increases.

The Nichols plots for these configurations (Figures 38 through 40) show that the highest achievable bandwidth for the altitude control loop increased from .43 rad/sec to .48 rad/sec as the pilot position was moved from 10 feet aft to 50 feet forward of the center of rotation.

The analysis of the Short Aft Tail configuration with higher shuttle effective time delay (T_1 = .35) showed a lower achievable bandwidth. The root locus (Figure 35) does not show much change for the T_1 = .35 versus $T_1 = A$ configuration but the Nichols plot (Figure 41) shows the bandwidth has decreased from .43 rad/sec to .33 rad/sec. The T_1 = .35 case also had a much higher inner loop lead (τ_L = 3.67 sec) than the $T_1 = A$ configuration (τ_L = .97 sec).

An analysis was also performed on the Extra-High q-augmented configuration to see what improvement the high augmentation gain would yield. The root locus (Figure 36) and Nichols plot (Figure 42) show lower altitude loop bandwidth (.38 rad/sec). However, the inner pitch attitude loop for the Extra-High q configuration had a lead time constant of only .21 sec instead of .97 sec for the High q configuration. This penalizes the altitude loop bandwidth since the pilot could most likely provide more lead. The lead provided in the

High q configuration at 1 rad/sec is $\tan^{-1}$ (.97)(1.) = 44 degs. The lead provided in the Extra-High q-augmented configuration at 1 rad/sec = $\tan^{-1}$ (.21)(1.) = 12 degrees. Therefore, to add an extra 32 degs of lead at ω = 1 rad/sec, a lead term of $\frac{\tan 32^o}{1\ \text{rad/sec}}$ = .63 sec was added to the altitude control pilot model:

$$Y_{P_h} = K_{P_h} \ (.63s + 1)$$

The result on the root locus (Figure 37) and Nichols plot (Figure 43) is a much higher bandwidth than was achieved with the High q configuration (.5 rad/sec versus .43 rad/sec). This increases the altitude loop bandwidth up to where it would have been for the High q-augmented configuration if the pilot had been shifted forward approximately 70 feet for an X_{MP} = 120 ft and X_{PCR} = 60 feet (see Figure 44 for ω_{BW_h} versus X_{PCR}). This was confirmed from the experiment results for the Extra-High q-augmented configuration (PR = 4) compared to those for the High q-augmented configuration with X_{MP} = 100 ft (PR = 3 and 4-1/2).

Pilot rating and pilot-induced oscillation rating are correlated with the calculated altitude loop bandwidth in Figures 45 and 46, the trend towards better ratings with high bandwidth can be seen. Though not enough samples were taken to absolutely define flying qualities boundaries, it appears that a bandwidth of greater than .5 rad/sec may be necessary for Level 1 ratings. This correlates well with data obtained by the Dutch in an NLR study (Reference 11). They used the same altitude control loop pilot model in a medium transport landing approach experiment, and proposed a .55 rad/sec altitude bandwidth as necessary for Level 1 flying qualities.

It is also interesting to note that by decreasing the effective time delay from .35 sec to .10 sec and increasing the q-augmentation level, the Short Aft Tail configuration with equivalent shuttle delay can be improved so that the altitude bandwidth increases from .33 rad/sec to .5 rad/sec. This assumes that the pilot could provide the required lead in the altitude loop. In the flight evaluations, these changes resulted in improved pilot ratings from 9 to 4 and PIO ratings from 4 to 2.

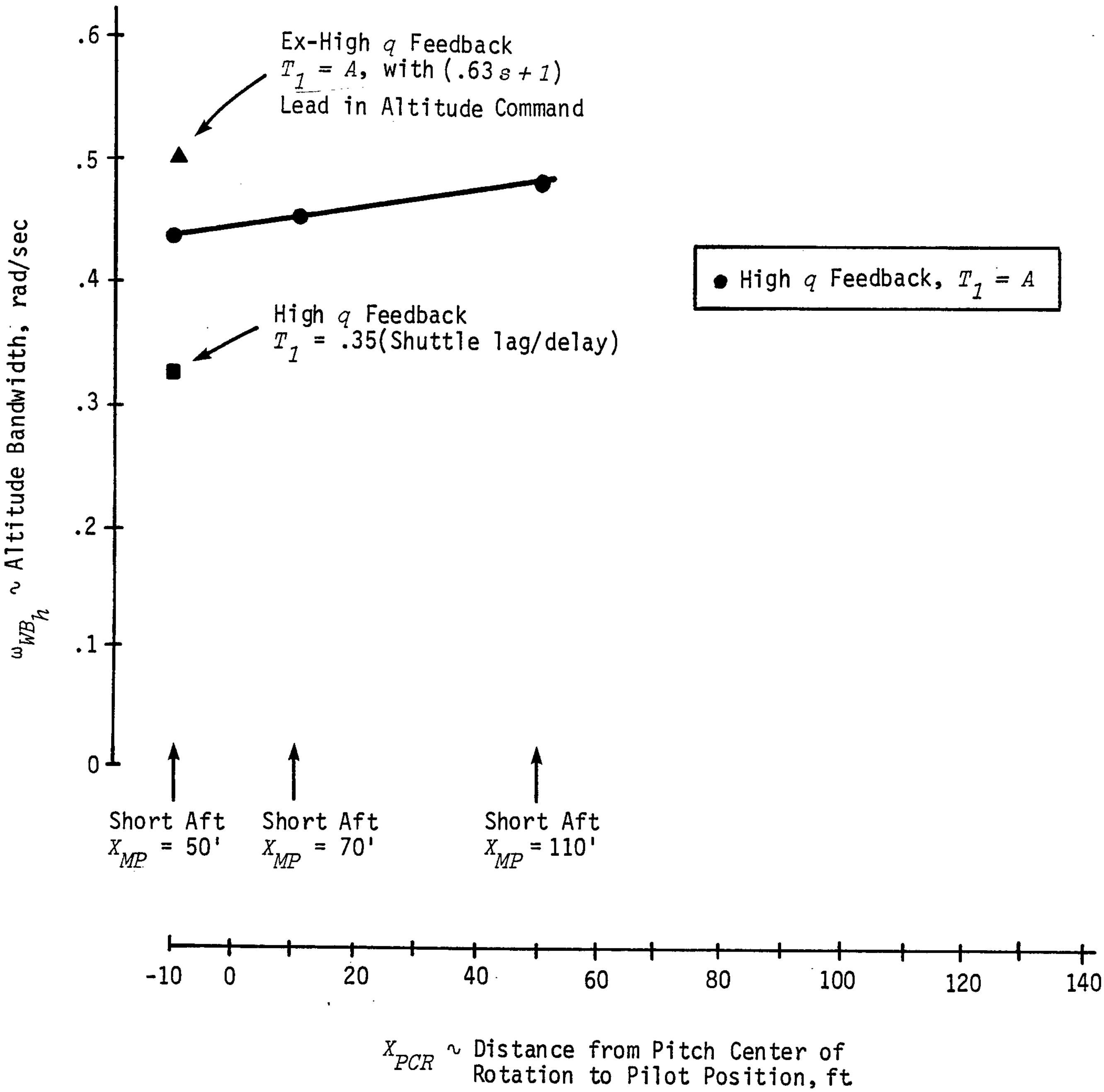


Figure 44. ALTITUDE BANDWIDTH VS PILOT POSITION - CENTER OF ROTATION (X_{PCR})

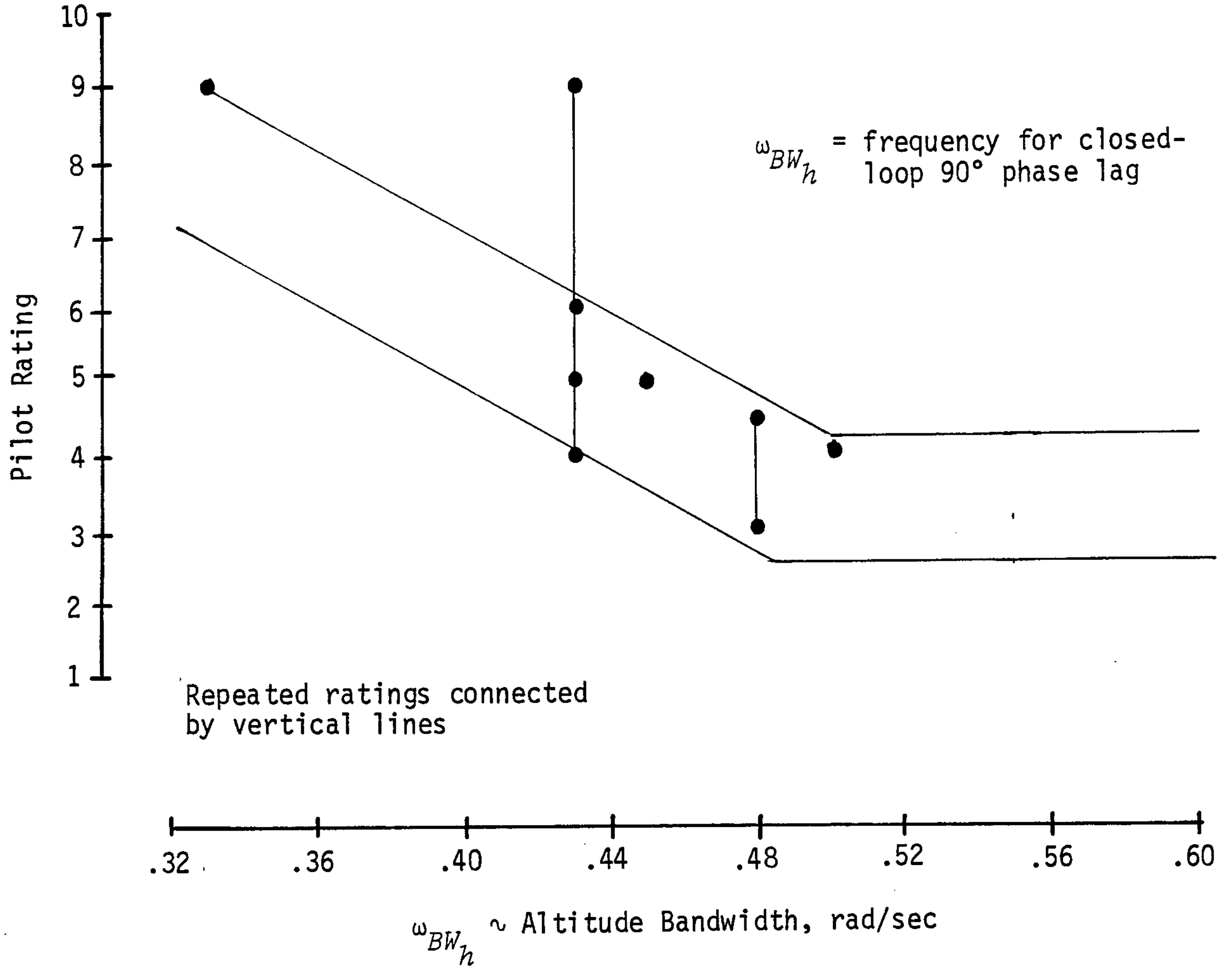


Figure 45. PILOT RATING VS ALTITUDE BANDWIDTH

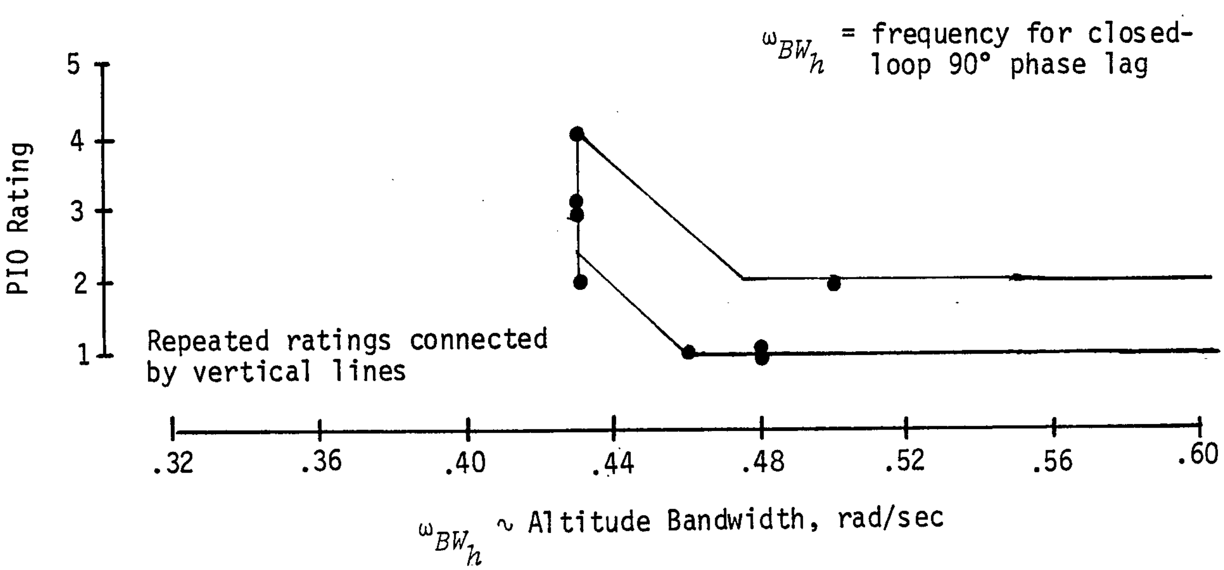


Figure 46. PIO RATING VS ALTITUDE BANDWIDTH

4.6 TURBULENCE RESPONSE

A thorough discussion of the effects of turbulence would be quite lengthy because the turbulence field has many comments and the airplane has many responses that could be considered. Several gust transfer functions are listed in Reference 13. For purposes of illustration, however, only two figures are considered. Figures 47 and 48 present the θ/α_g and V_I/α_g frequency responses for the following Short Aft Tail configurations — Unaugmented, High α feedback and High q feedback. These transfer functions show that in the low range of frequency, i.e., less than 1.0 rad/sec, the High α-augmented configuration is the most responsive to turbulence, while the High q-augmented configuration is the least responsive. The unaugmented configuration is between the two in its level of response to the α gusts.

The large variation of the pitch attitude and inertial speed responses to angle of attack gust inputs exhibited in Figures 47 and 48 at low frequency is caused by the effect of the augmentation system on both the denominator and the numerators of the gust transfer functions. The low frequency factors of the θ/α_g transfer function for the three configurations illustrated on Figure 47 are as follows:

$$\frac{\theta}{\alpha_{g_{High\ q}}} = \frac{.35(0)(.034)}{(.041)[.66,.73](1.30)} \quad \text{(higher frequency terms)}$$

$$\frac{\theta}{\alpha_{g_{Unaug}}} = \frac{.35(0)(.036)}{(-.183)[.37,.21](1.15)} \quad \text{(higher frequency terms)}$$

$$\frac{\theta}{\alpha_{g_{High\ \alpha}}} = \frac{.35(.057)(.931)}{[.054,.126][.77,.79]} \quad \text{(higher frequency terms)}$$

Although literal expressions for the gust transfer function numerators have not been developed for the various augmentation configurations, it is clear from the numerical examples listed above and in Appendix I that the effects of the augmentation system on the transfer function numerators

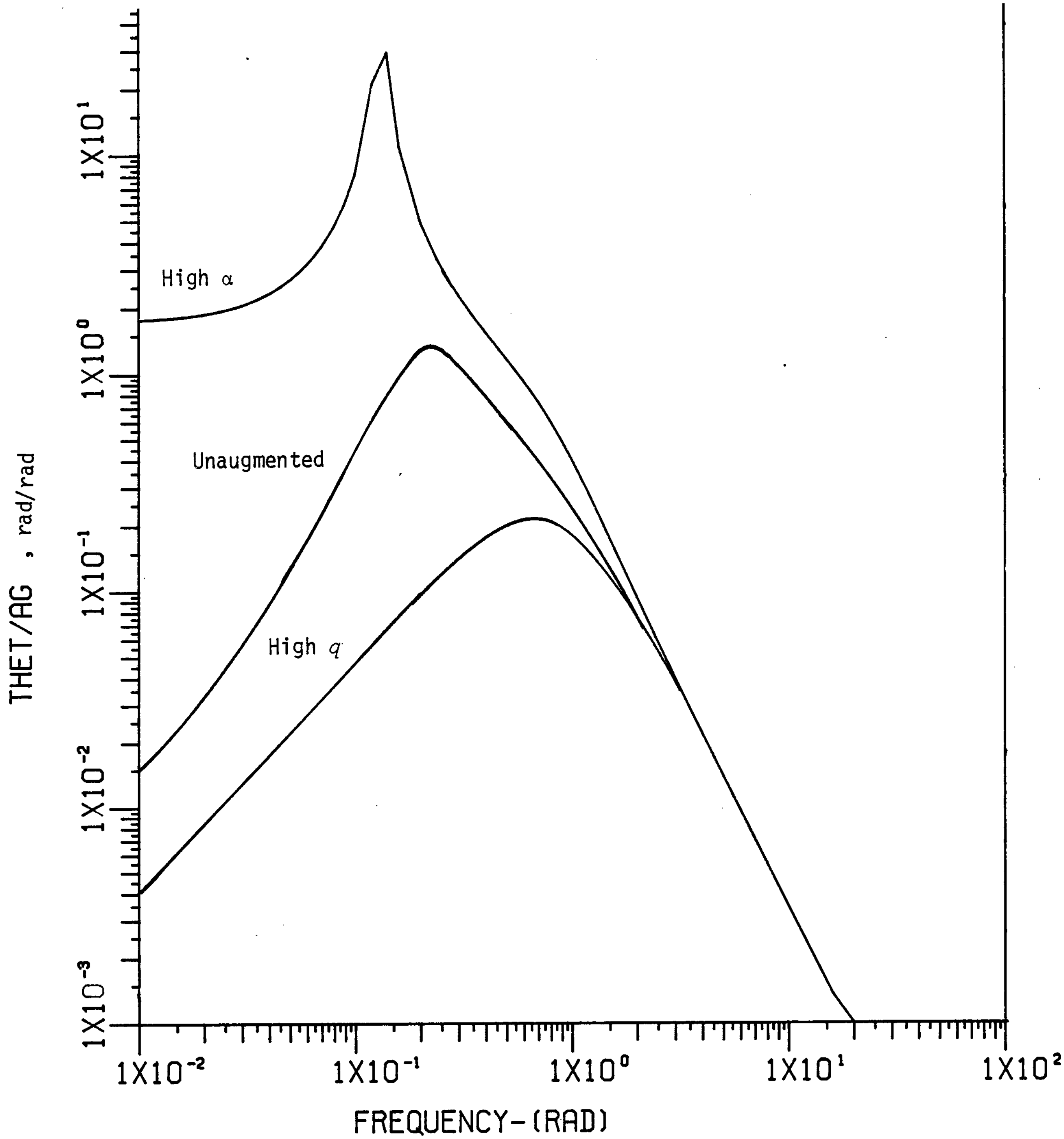


Figure 47. SHORT AFT TAIL, TURBULENCE RESPONSE, θ/α_g

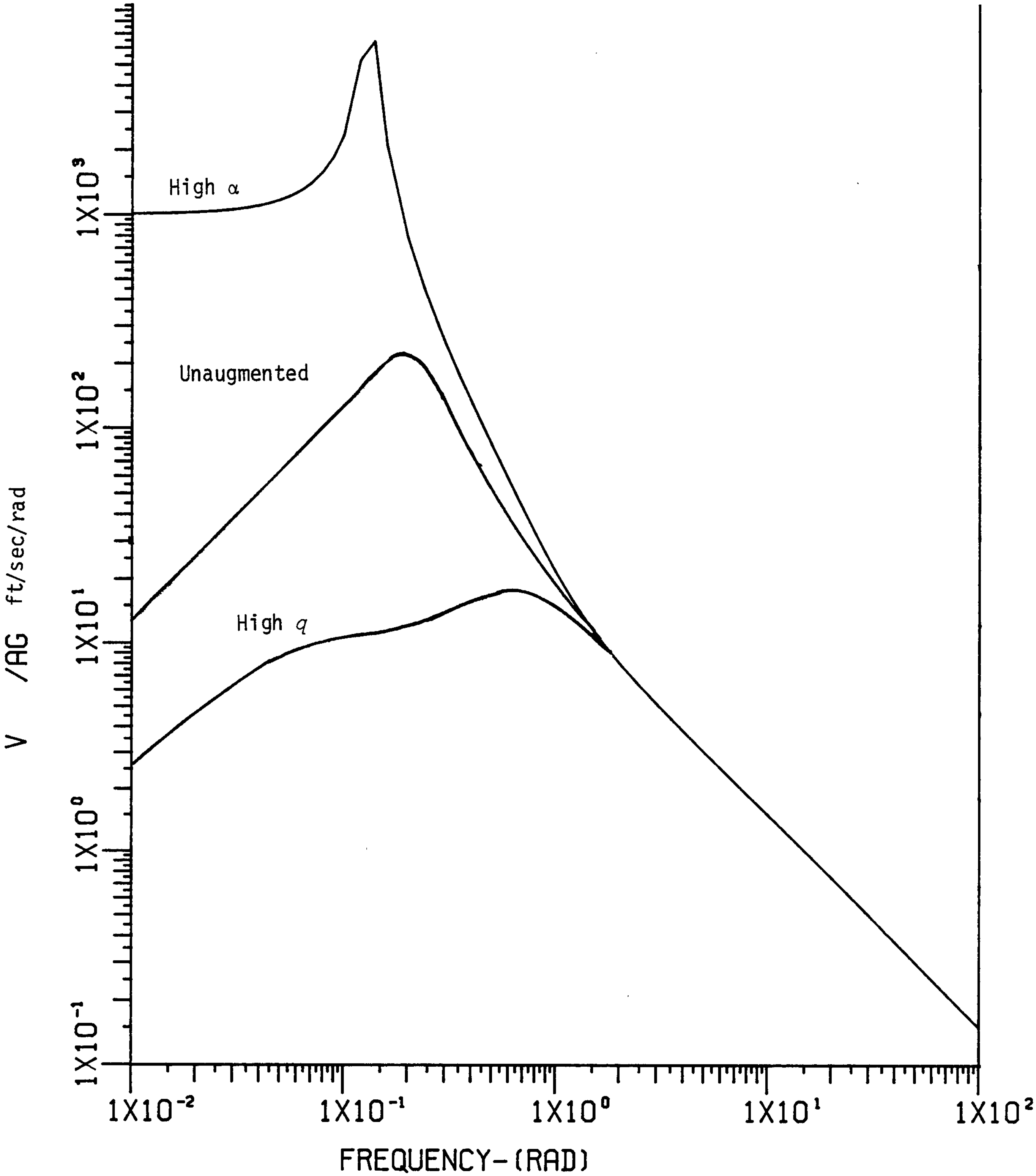


Figure 48. SHORT AFT TAIL TURBULENCE RESPONSE, V/α_g

is significant and must be considered together with the effect on the characteristic equation.

The comments by the evaluation pilots concerning the responses of the various configurations to turbulence are generally consistent with the characteristics exhibited on Figures 47 and 48 and with other gust transfer functions not illustrated by figures. Note that the pilot comments are in terms of observation of airspeed whereas the transfer function illustrated in Figure 48 is for the inertial velocity response to angle of attack gusts.

All of the configurations were described as slightly ponderous in turbulence. This was due to the low short period frequency of all of the stable configurations. With the higher α-augmented configurations, the pilots complained about the attitude disturbances in turbulence. They described the airplane as being very ponderous and hard to manage on the ILS and the increased workload required in the pitch axis was objectionable. It took a long time to correct disturbances in speed and pitch attitude. With the higher q-augmented configurations, turbulence was noticed, but the pilots said they did not have to do anything and it was not a problem.

Lateral-directionally, all of the configurations received comments about their wallowing nature in turbulence. This was primarily due to their low total damping, $\zeta_d\omega_d$ = .28, and time to half amplitude of approximately 2.5 seconds. This, along with the high rudder forces, made it difficult to damp out the sideslip excited in turbulence. Roll motions were also noted by the pilots in turbulence, but was generally not a problem.

4.7 DIRECT LIFT CONTROL

As the flight evaluation program continued, it became obvious that the Short Aft Tail configurations were presenting the pilots extreme flight path control problems as they neared the ground. Many of the approaches, even with minimum levels of delay, resulted in PIO's in the flare maneuver. PIO ratings of 3 or worse were the rule with the high augmented configurations. The problem was basically due to the fact that the pilot was sitting

ten feet behind the pitch center of rotation in these configurations. The pilot would use his pitch control to bend the flight path to reduce his rate of sink in the flare. The immediate effect was a sinking motion, perhaps causing him to overcontrol. When pushing forward, the opposite would happen — the aircraft would tend to heave up as it rotated nose down. This rapidly degenerated into a PIO or the pilot had to abandon the task and settle for very long, unacceptable touchdowns.

It was speculated that if the pilots had a direct control for flight path angle that did not require the aircraft to rotate, the PIO's could be eliminated and pilot ratings improved. A direct lift controller that produced pure lift without pitching moment or drag was included in the model for this purpose. It was operated from a thumb wheel on the throttle handle. Full deflection of the wheel ($\pm 160^{\circ}$) produced a ΔC_L of $\pm .3$. This translated to a $\pm .2$ g capability at 150 KIAS. There was no force/feel on this controller, but a slight detent could be felt around the zero deflection point. Rotating the wheel upward resulted in positive lift. A $\frac{1}{.1s+1}$ filter was added to eliminate inadvertent high frequency commands. The direct lift controller (DLC) was evaluated with the High α and High q-augmented configurations by one of the pilots.

Results of this limited evaluation were encouraging. After a couple of approaches to learn how to use the DLC, the pilot felt he had a better control over sink rate in the flare. Pilot rating and PIO rating improvements are shown in Table X. The pilot used the DLC only in the flare portion of the approach for sink rate control. He used the pitch controller in the upper portion of the approach and for attitude control in the flare and touchdown. He described his major difficulties as learning how to use four controllers (elevator, aileron, throttle, and DLC) at the same time, and knowing how much lift control he had in at a particular moment. He felt more experience with the controller and a force/feel system or at least a centering spring may have improved his opinion of the DLC.

TABLE X

PILOT RATING AND PIO RATING

COMPARISONS FOR DIRECT LIFT CONTROL

Configuration: Short Aft Tail $X_{MP} = 50$ feet $T_1 = A$	Pilot Rating		PIO Rating	
	No DLC	With DLC	No DLC	With DLC
High α Feedback	9,8	6	5,4	3
High q Feedback	9,5	5	4,3	2

Section 5
CONCLUSIONS

1. The pilot rating and comment data exhibit significant effects of the following experiment variables:

   - Augmentation type and level of loop gain, i.e., angle of attack feedback or pitch rate feedback with proportional plus integral in forward path and automatic elevator for turns.
   - Pilot location relative to the center of rotation for elevator commands.
   - Lag and time delay in the command path for both pitch and roll.
   - Slow thrust response coupled with backside aerodynamic characteristics.
   - Direct lift control.

   Neither the MIL-F-8785C requirements nor any of several proposed requirements for pitch and control system dynamics were capable of correlating the experiment results without significant modification or extension.

2. The pitch rate augmentation system was generally preferred over the angle of attack augmentation. This was especially true for the Short Aft Tail configurations with the pilot behind the center of rotation. This was due to the lower turbulence response, attitude-hold feature, and level turn capability without pitch inputs with the q-augmented configurations.

3. The pilot ratings were degraded for the cases where the pilot was located near or behind the center of rotation.

4. The evaluation pilots tended to apply a less demanding standard of maneuverability than for previous landing approach studies because the configurations were defined to be very large, one-million pound, Class III aircraft. The closed-loop pitch attitude bandwidth requirements for the landing approach task with this Class of aircraft appears to be 1.5 rad/sec.

5. The degradation caused by time delay was less severe than in previous landing approach studies, in both pitch and roll. This is primarily a result of the decreased bandwidth demanded by the pilots for this class airplane. The present equivalent time delay requirements of MIL-F-8785C appear to be conservative for this class of airplane and flight phase. Data is presented which suggests that the amount of time delay that can be tolerated in the command path is inversely related to the dynamic bandwidth required to perform the task.

6. When the pilot position is forward of the center of rotation, the pitch acceleration response to control provides an earlier linear acceleration cue at the pilot position that is easily perceived by the pilot and serves to confirm to the pilot that the airplane is responding to his command. When the pilot is located far ahead of the center of rotation, the linear acceleration cue is amplified immediately following the transmission delay through the control system but before the lag associated with the short period mode. This effect may contribute to the higher tolerance to control system time delay observed in this experiment.

7. A multi-loop analysis which modeled an outer altitude control loop in series around the inner pitch attitude loop provided insight into the effects of pilot location relative to the center of rotation. A low-frequency closed-loop pole goes unstable at relatively low gain and frequency with the pilot aft of the center of rotation. As the pilot moves further forward of the center of rotation, this complex mode remains stable and closed-loop bandwidth of the altitude control loop increases. A closed-loop altitude bandwidth of .5 rad/sec appears necessary for

Level 1 ratings. For the Short Aft Tail configurations, it was shown that increasing the level of q-augmentation had a similar effect on altitude bandwidth as moving the pilot forward.

8. Evaluation of the shuttle-like Short Aft Tail configuration with the pilot located ten feet behind the center of rotation indicated acceptable flying qualities could be achieved when the command path time delay was low and the Extra-High pitch rate augmentation was used. This aircraft design was unacceptable when time lag and delay equal to that of the shuttle was introduced into the pitch command path and the High pitch rate augmentation was used.

9. The effect of turbulence on the unaugmented configurations was relatively low except for long-term speed control due to its negative static stability. As the α-augmentation level was increased, pitching and airspeed response to turbulence became greater at frequencies below 1 rad/sec. At the highest levels of augmentation, the response to turbulence at low frequency seriously hindered control. The effect of the pilot being very far from the center of rotation also added to the motion felt by the pilot in turbulence. As the q-augmentation level was increased, these turbulence effects became less. This was due to the low static stability of the base airplane and the long term attitude hold of the q-feedback configurations.

10. The slow thrust response (three second time constant) to throttle caused difficulty in thrust management and forced open-loop manipulation of the throttles, i.e., set and wait to see if further adjustment is required. This complicated airspeed control and degraded the pilot ratings, especially for the α-augmented configurations. The slow thrust response compounded airspeed control for the Short Aft Tail designs which were slightly on the "backside" at the trim speed.

11. Direct lift control, commanded by a thumb wheel, mounted on the throttle lever, improved control of sink rate during flare and touchdown for the Short Aft Tail configuration. More pilot experience and a force/feel

system with the direct lift control would be necessary for a thorough evaluation.

12. The lateral-directional augmentation system provided excellent turn coordination and minimal excitation of sideslip in turning maneuvers.

13. The low frequency Dutch roll mode excited by turbulence, lineup, and crosswind corrections, required a special trimming technique and the response to rudder pedal inputs was slow. Rudder forces to maneuver were heavy.

Section 6
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13. Weingarten, N. C. and Chalk, C. R.: "In-Flight Investigation of Large Airplane Flying Qualities for Approach and Landing," Calspan Report No. 6645-F-5 (AFWAL-TR-81-3118), July 1981.

Appendix I
TRANSFER FUNCTIONS

The following is a tabulation of important transfer functions of the Short Aft Tail configurations. It is written in the shorthand notation where:

$$K(a)[\zeta,\omega] \text{ is equivalent to } K(s+a)[s^2 + 2\zeta\omega s + \omega^2]$$

The following factors are present in each of the longitudinal denominators:

Approximately	(20)	=	elevator servo	
	(.333)	=	throttle servo	
	[.7,25]	=	pitch control feel system	As noted
	[.7,15]	=	" " " "	

The lateral-directional denominators contain the following factors:

(20)	=	aileron or rudder servo
[.7,25]	=	roll control feel system
[.7,15]	=	yaw control feel system

The following gradients and gearings are present in the numerator gains:

	Gradient	Gearing
Pitch	.1 inch/pound	2.5 deg/inch (α-feedback) 1.25 deg/inch (q-feedback)
Roll	2. deg/pound	1.5 deg/deg (τ_R = .87) 3.0 deg/deg (τ_R = .44)
Yaw	.01 inch/pound	-15. deg/inch

In addition to the transfer function factors shown, the following delay/lag factors should be added to represent the level of delay flown in each axis:

	Delay Level	Additional Transfer Function Factors and Description	
Pitch	A	$e^{-.06s}$	TIFS pitch model-following delay = .06 sec
	B	$\frac{9.e^{-.06s}}{(9)}$	"A" plus command filter $\frac{1}{.111s+1}$
	C	$\frac{9.e^{-.13s}}{(9)}$	"B" plus extra command delay = .07 sec
	C'	$\frac{9.e^{-.24s}}{(9)}$	"B" plus extra command delay = .18 sec (Equivalent to shuttle lags)
Roll	A	$e^{-.12s}$	TIFS roll model-following delay = .12 sec

All angular units in radians, velocity in ft/sec.

LONGITUDINAL TRANSFER FUNCTIONS

<u>CONFIGURATION:</u> Short Aft Tail α-Feedback, K_α=-.85 (Medium)

Denominator [.927,.630][.148,.0956](20)(.333)[.7,25.]

$N^{\theta}_{F_{ES}}$ 2.30 (.527)(.059)(.333)

$N^{\alpha}_{F_{ES}}$ .545 [.065,.170](4.84)(.333)

$N^{V_I}_{F_{ES}}$ 8.20 (.975)(-5.16)(.333)

$N^{N_{zp}(50')}_{F_{ES}}$ .726 (4.24)(-.0037)(-3.29)(0)(.333)

$N^{N_{z_{CG}}}_{F_{ES}}$ 4.29 (1.89)(-.0037)(-1.24)(0)(.333)

$N^{V_I}_{\delta_T}$ 2.13 [.934,.625](0)(20)[.7,25.]

$N^{\dot{h}_{CG}}_{\delta_T}$ .542 [.895,.334](20)[.7,25.]

CONFIGURATION: Short Aft Tail α-Feedback, K_α=-1.25 (High)

Denominator [.773,.788][.0539,.126](20)(.333)[.7,25.]

F_{ES} Numerators - same as those for Medium

$N^{V_I}_{\delta_T}$ 2.13 [.774,.777](0)(19.9)[.7,25.]

$N^{\dot{h}_{CG}}_{\delta_T}$ .542 [.536,.549](20)[.7,25.]

CONFIGURATION: Short Aft Tail q-Feedback, T_q=1, K_q=-1.05 (Medium)

Denominator [.395,.503](1.19)(.0194)(0)(19.5)(.333)[.7,25.]

$N^{\theta}_{F_{ES}}$ 1.21 (.527)(.059)(1)(.333)

$N^{\alpha}_{F_{ES}}$ .286 [.0647,.170](4.84)(1)(.333)

$N^{V_I}_{F_{ES}}$ 4.30 (.975)(-5.16)(1)(.333)

$N^{N_{zp}(50')}_{F_{ES}}$ .381 (4.24)(-.0037)(-3.29)(0)(1)(.333)

$N^{N_{z_{CG}}}_{F_{ES}}$ 2.25 (1.89)(-.0037)(-1.24)(0)(1)(.333)

$N^{V_I}_{\delta_T}$ 2.13 [.405,.483](1.19)(0)(19.5)[.7,25.]

$N^{\dot{h}_{CG}}_{\delta_T}$ .542 (.878)(.241)(0)(19.5)[.7,25.]

CONFIGURATION: Short Aft Tail q-Feedback, $T_q=1$, $K_q=-2.5$ (High)

Denominator [.666,.727](1.305)(.0408)(0)(18.8)(.333)[.7,25.]

$N^{\theta}_{F_{ES}}$ 2.87 (.527)(.0593)(1)(.333)

$N^{\alpha}_{F_{ES}}$ .681 [.0647,.170](4.84)(1)(.333)

$N^{V_I}_{F_{ES}}$ 10.25 (.975)(-5.16)(1)(.333)

$N^{N_{zp}(50')}_{F_{ES}}$ .907 (4.24)(-3.29)(-.0037)(0)(1)(.333)

$N^{N_z(70')}_{F_{ES}}$ -.903 [.030,3.75](-.0037)(0)(1)(.333)

$N^{N_z(110')}_{F_{ES}}$ -4.47 [.152,1.70](-.0036)(0)(1)(.333)

$N^{N_{z_{CG}}}_{F_{ES}}$ 5.36 (1.89)(-1.24)(-.0037)(0)(1)(.333)

$N^{V_I}_{\delta_T}$ 2.13 [.680,.724](1.30)(0)(18.8)[.7,25.]

$N^{\dot{h}_{CG}}_{\delta_T}$ .542 [.951,.976](0)(18.8)[.7,25.]

CONFIGURATION: Short Aft Tail q-Feedback, $T_q=.5$, $K_q=-5.2$ (Extra High)

Denominator [.671,2.212](.597)(.0547)(0)(17.5)(.333)[.7,25.]

$N^{\theta}_{F_{ES}}$ 5.98 (.527)(.0593)(2)(.333)

$N^{\alpha}_{F_{ES}}$ 1.42 [.0647,.170](4.84)(2)(.333)

$N_{F_{ES}}^{V_I}$ 21.3 (.975)(-5.16)(2)(.333)

$N_{F_{ES}}^{N_{zp}(50')}$ 1.89 (4.24)(-.0037)(-3.29)(0)(2)(.333)

$N_{F_{ES}}^{N_{z_{CG}}}$ 11.15 (1.89)(-.0037)(-1.24)(0)(2)(.333)

$N_{\delta_T}^{V_I}$ 2.13 [.671,2.213](.622)(0)(17.5)[.7,25.]

$N_{\delta_T}^{\dot{h}_{CG}}$ .542 [.698,2.31](0)(17.4)[.7,25.]

LATERAL-DIRECTIONAL TRANSFER FUNCTIONS

$Z_{sp} = -18'$

CONFIGURATION: $\tau_R = .87$

Denominator [.574,.486](1.15)(.0034)(20)[.7,25.](20)[.7,15.]

$N_{F_{AS}}^{\phi}$ 15.6 [.570,.483](19.8)[.7,15.]

$N_{F_{AS}}^{r}$ .756 [.589,.477](3.45)(14.9)[.7,15.]

$N_{F_{AS}}^{\beta}$ -.0089 (.331)(-.226)(-27.9)(12.2)[.7,15.]

$N_{F_{AS}}^{N_y(50')}$ 8.13 [.590,.479](.256)(-.211)(19.5)[.7,15.]

$N_{F_{AS}}^{N_y(70')}$ 7.92 [.592,.478](.364)(-.155)(19.2)[.7,15.]

$N_{F_{AS}}^{N_y(110')}$ 7.30 [.591,.475](.684)(-.093)(18.7)[.7,15.]

$N_{F_{RP}}^{\phi}$	-.162 (1.47)(-1.14)(18.6)[.7,25.]
$N_{F_{RP}}^{r}$	.459 [.0507,.244](1.17)(19.7)[.7,25.]
$N_{F_{RP}}^{\beta}$	-.050 (9.61)(1.16)(.0048)(19.7)[.7,25.]
$N_{F_{RP}}^{N_y(50')}$	.244 [.059,1.00](1.05)(-.024)(20)[.7,25.]
$N_{F_{RP}}^{N_y(70')}$	.541 [.056,.685](1.11)(-.022)(19.8)[.7,25.]
$N_{F_{RP}}^{N_y(110')}$	1.125 [.044,.500](1.14)(-.019)(19.7)[.7,25.]

Appendix II
TIME HISTORIES

This appendix presents time histories for each of the Short Aft Tail configurations for step inputs into the pitch, roll, and yaw command channels. Feel system dynamics, model-following delay, and extra time delay and lags were not included. Magnitude of inputs and command gains used were:

pitch – 1. inch through 1. deg/inch gain

roll – 1. deg through 1. deg/deg gain

yaw – 1. inch through 1. deg/inch gain

Notation used in the body axes system is:

Longitudinal –

Q – (q) – pitch rate, rad/sec
V – (ΔV) – incremental true airspeed, ft/sec
ALFA – ($\Delta\alpha$) – incremental angle of attack, rad
*Q** – ($\dot{q}$) – pitch acceleration, rad/sec^2
NZCG – ($n_{z_{CG}}$) – normal acceleration at center of gravity, g's
NZP – (n_{z_p}) – normal acceleration at nominal pilot station, g's
X_{MP} = 110 ft for Long Aft Tail and Canard
X_{MP} = 50 ft for Short Aft Tail
NZ50, NZ70, N110 – normal acceleration at shifted pilot position
X_{MP} = 50, 70, 110 ft for the configuration shown, g's

Lateral-Directional –

P – (p) – roll rate, rad/sec
R – (r) – yaw rate, rad/sec
BETA – (β) – sideslip, rad

PHI — (ϕ) — bank angle, rad

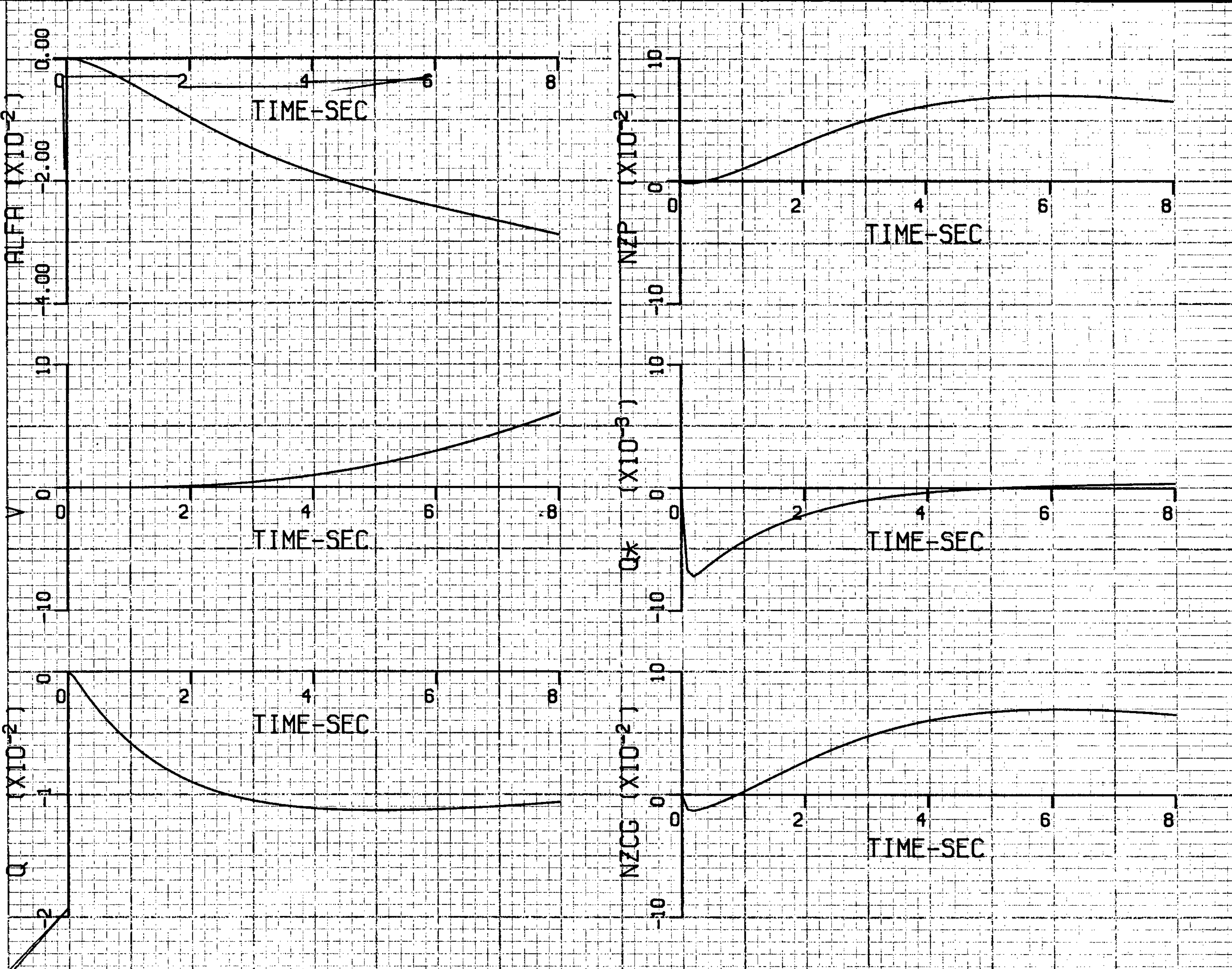
*P** — ($\dot{p}$) — roll acceleration, rad/sec

*R** — ($\dot{r}$) — yaw acceleration, rad/sec

NYCG — ($n_{y_{CG}}$) — lateral acceleration at center of gravity, g's

NY50, 70, 110 — lateral acceleration at nominal pilot height above stability axis (Z_{sp} = -18 ft) and X_{MP} = 50, 70, 110 ft, g's

Note that scalings may change from one configuration to another.



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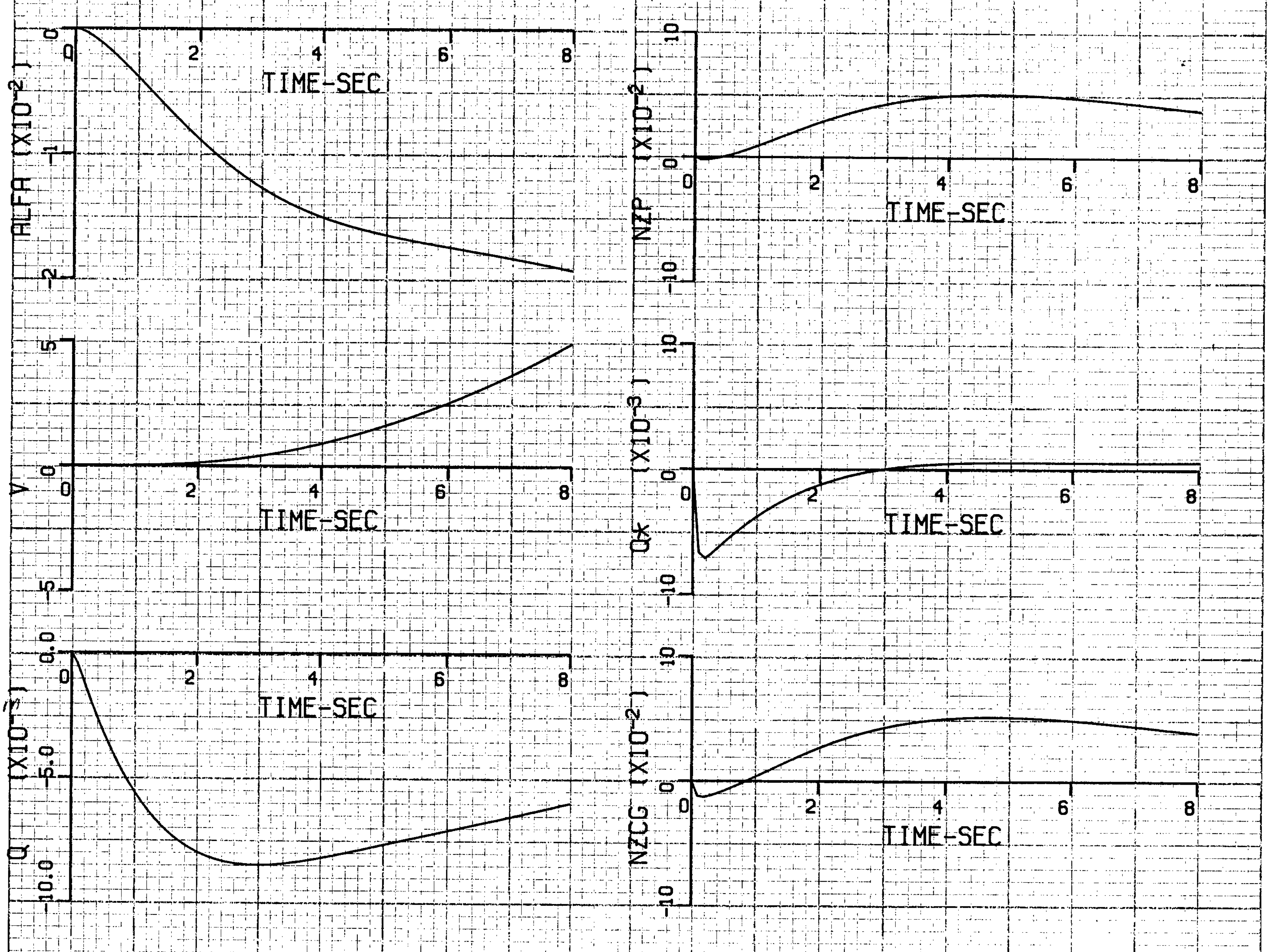

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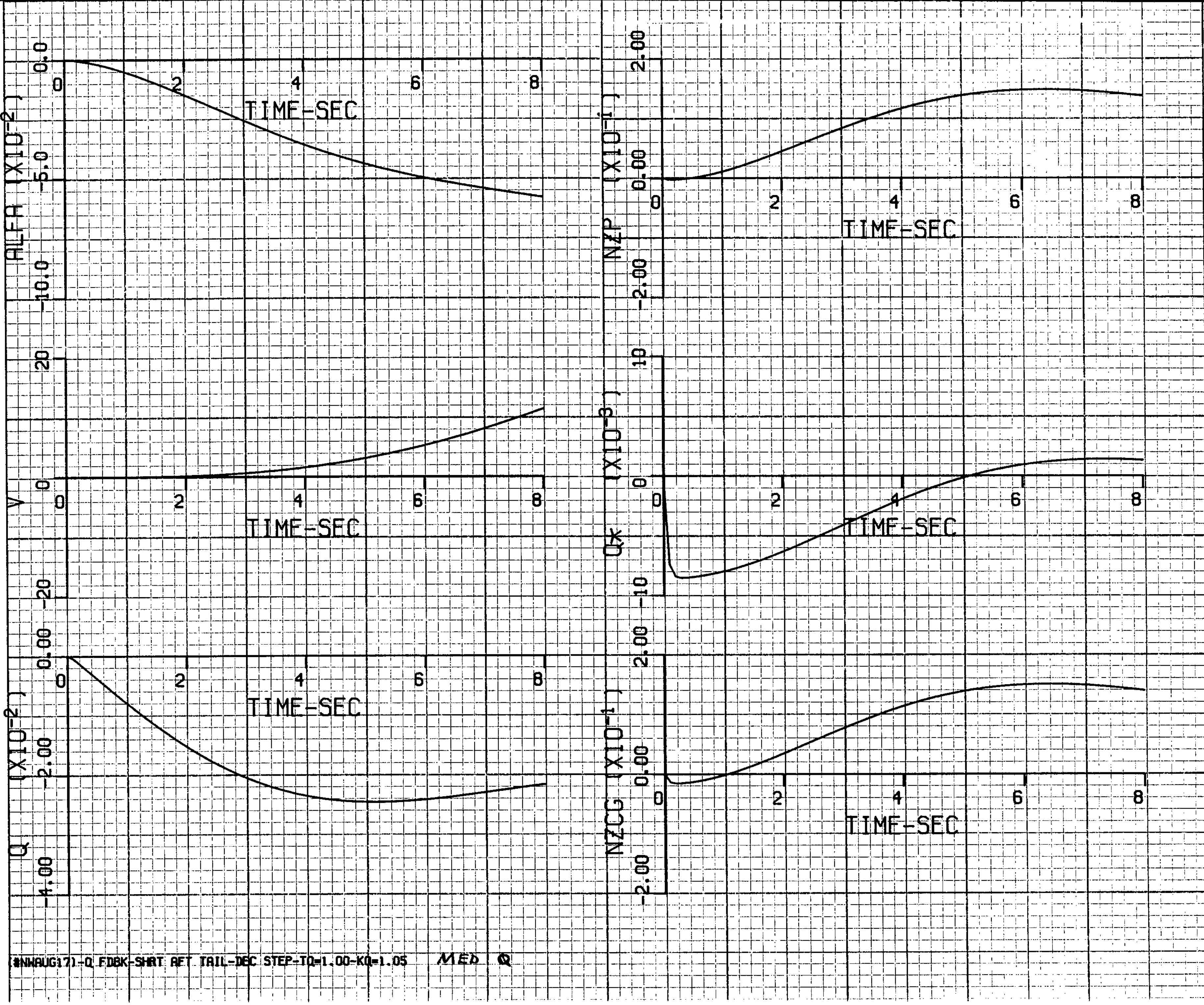
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-10.0
V
20
0
-20
Q (X10^-2)
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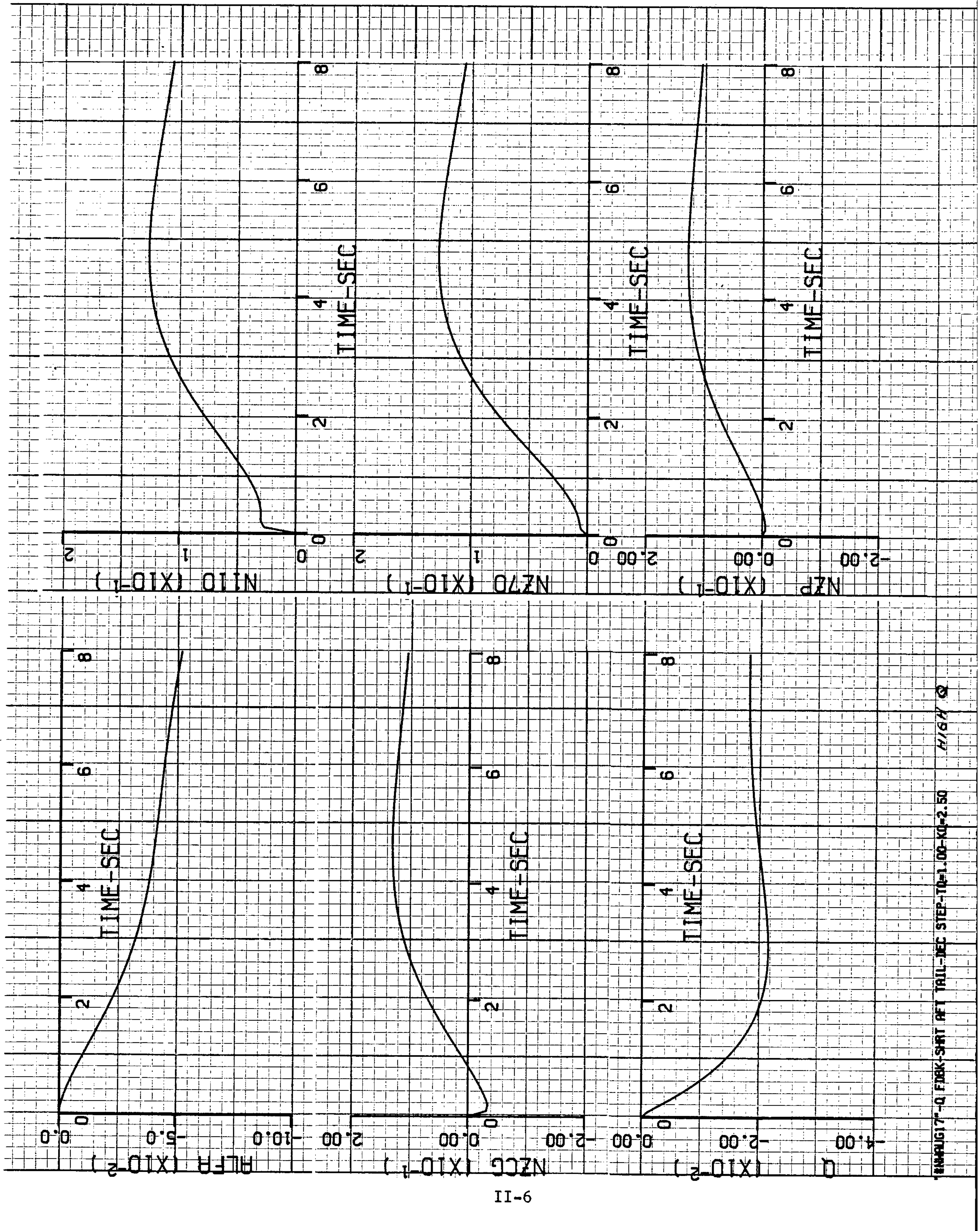
-2.00
-4.00
NZP (X10^-1)
2.00
0.00
-2.00
Q* (X10^-3)
10
0
-10
NZCG (X10^-1)
2.00
0.00
-2.00
0
2
4
6
8
TIME-SEC
(#NWAUG17)-Q FDBK-SHRT AFT TAIL-DEC STEP-TQ=1.00-KQ=1.05
MED Q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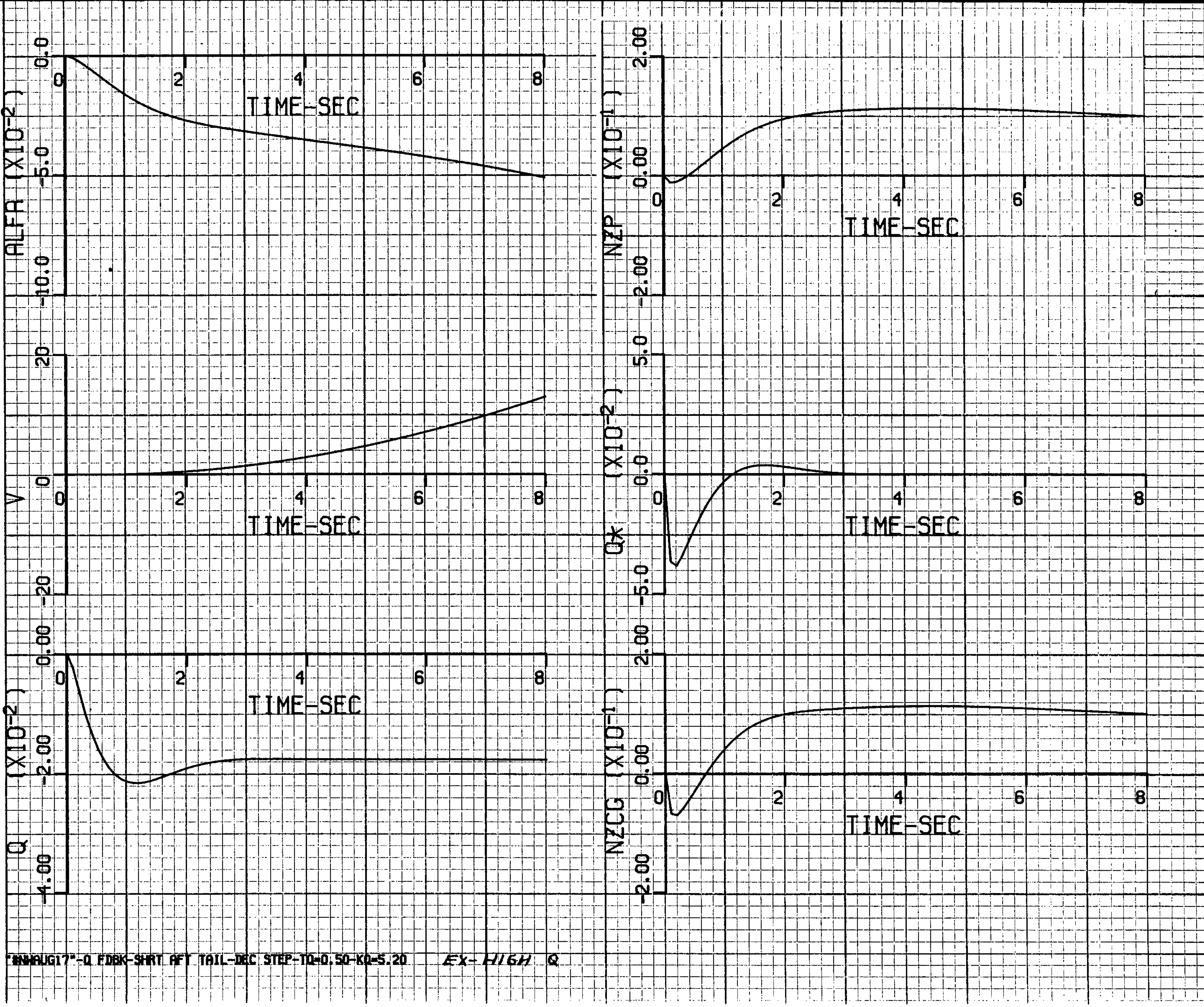
NZCG (X10-1)
Q (X10-2)
N11D (X10-1)
NZ7D (X10-1)
NZP (X10-1)
TIME-SEC
HIGH Q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-10.0
TIME-SEC
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2
4
6
8
V
20
0
-20
TIME-SEC
Q (X10-2)
0.00
-2.00
-4.00
TIME-SEC
NZP (X10-1)
2.00
0.00
-2.00
TIME-SEC
Q* (X10-2)
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0.0
-5.0
TIME-SEC
NZCG (X10-1)
2.00
0.00
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TIME-SEC
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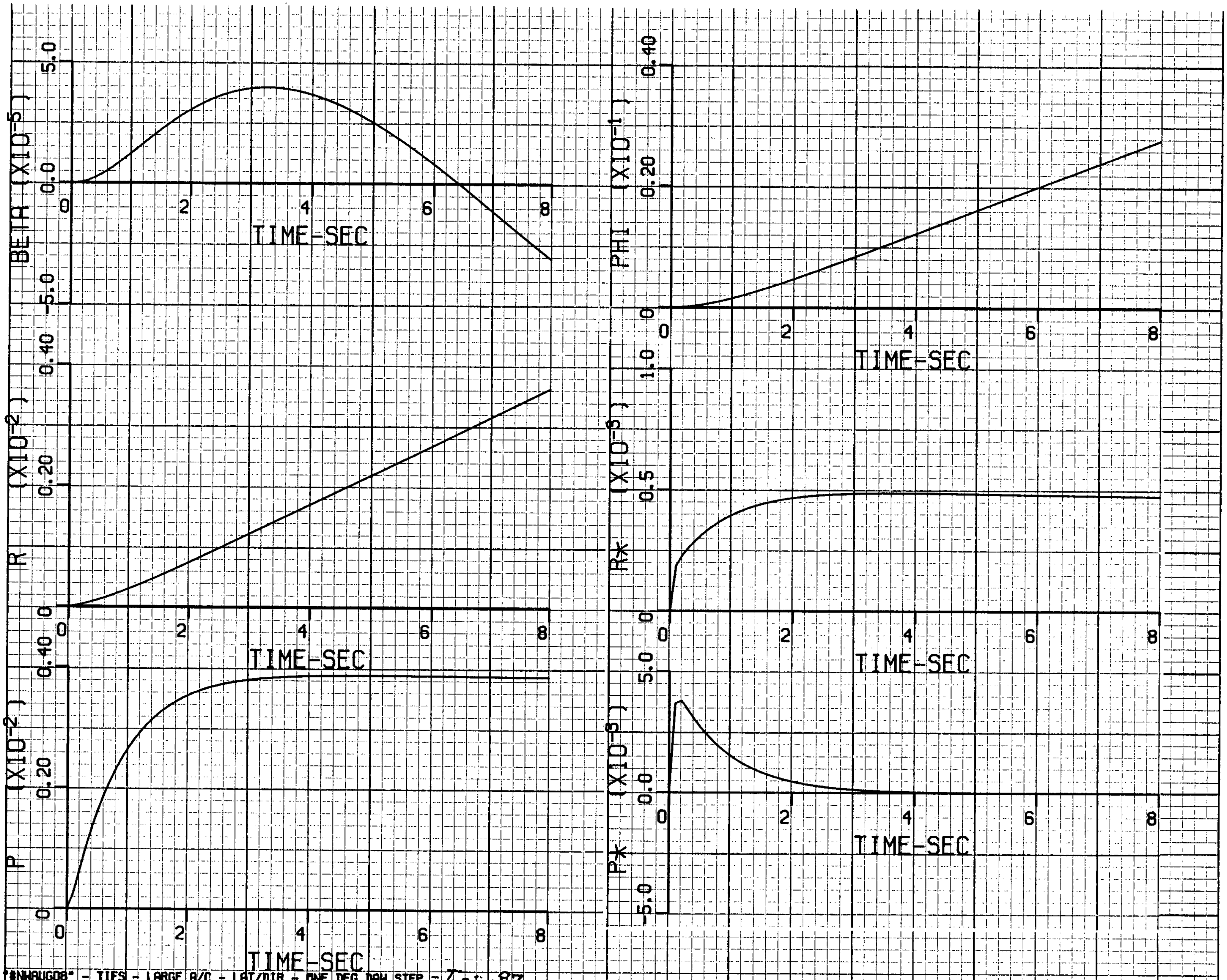
EX- HIGH Q



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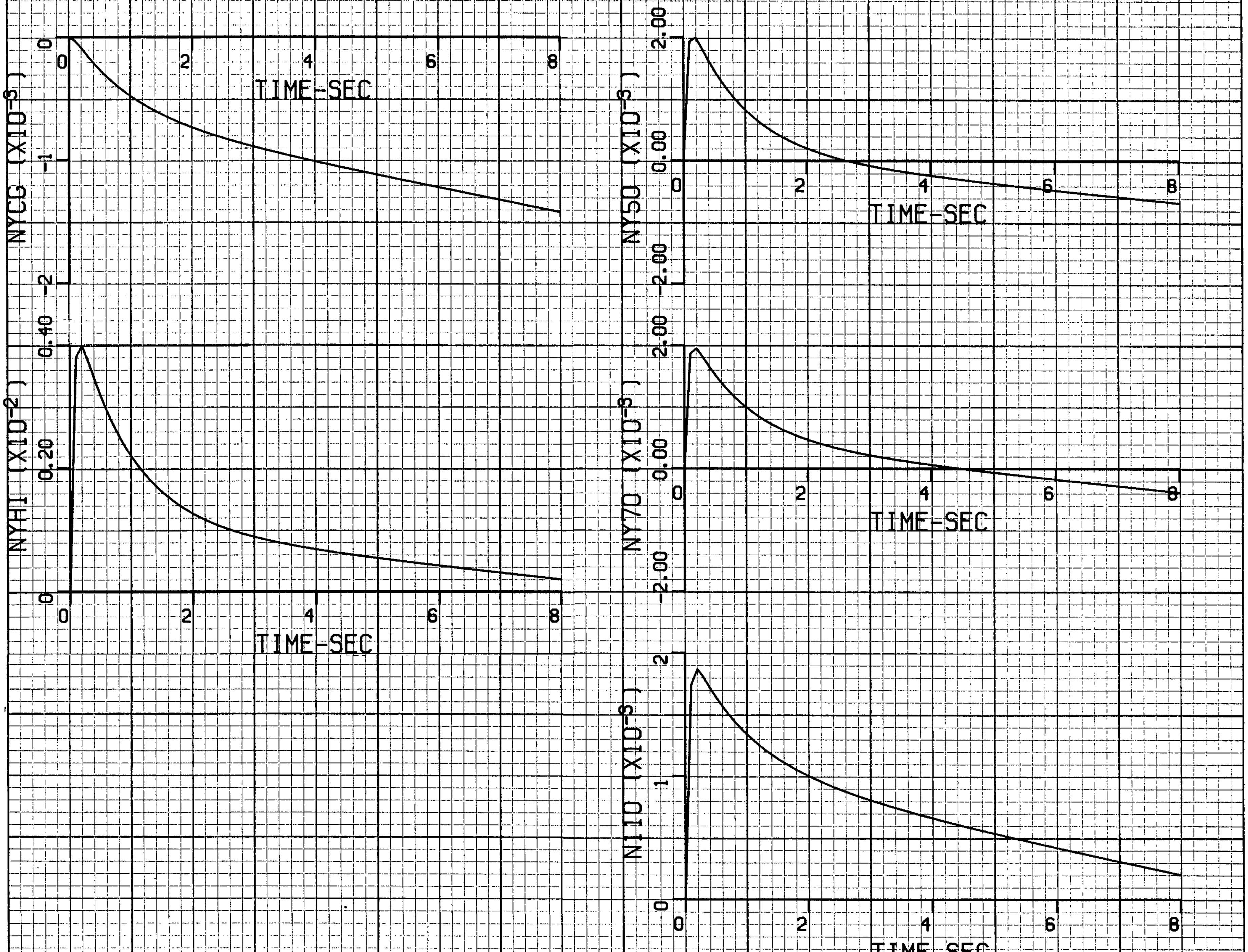
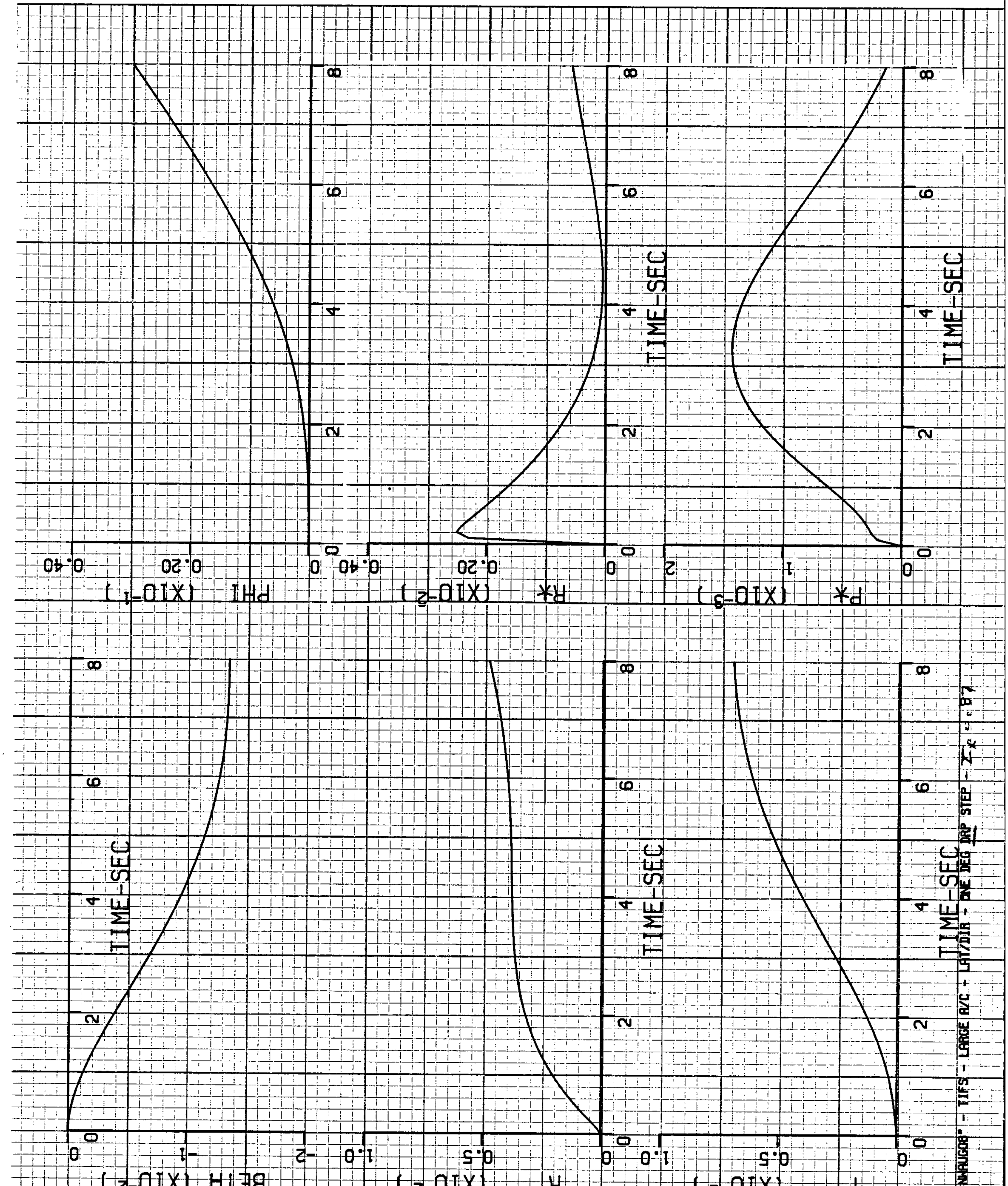
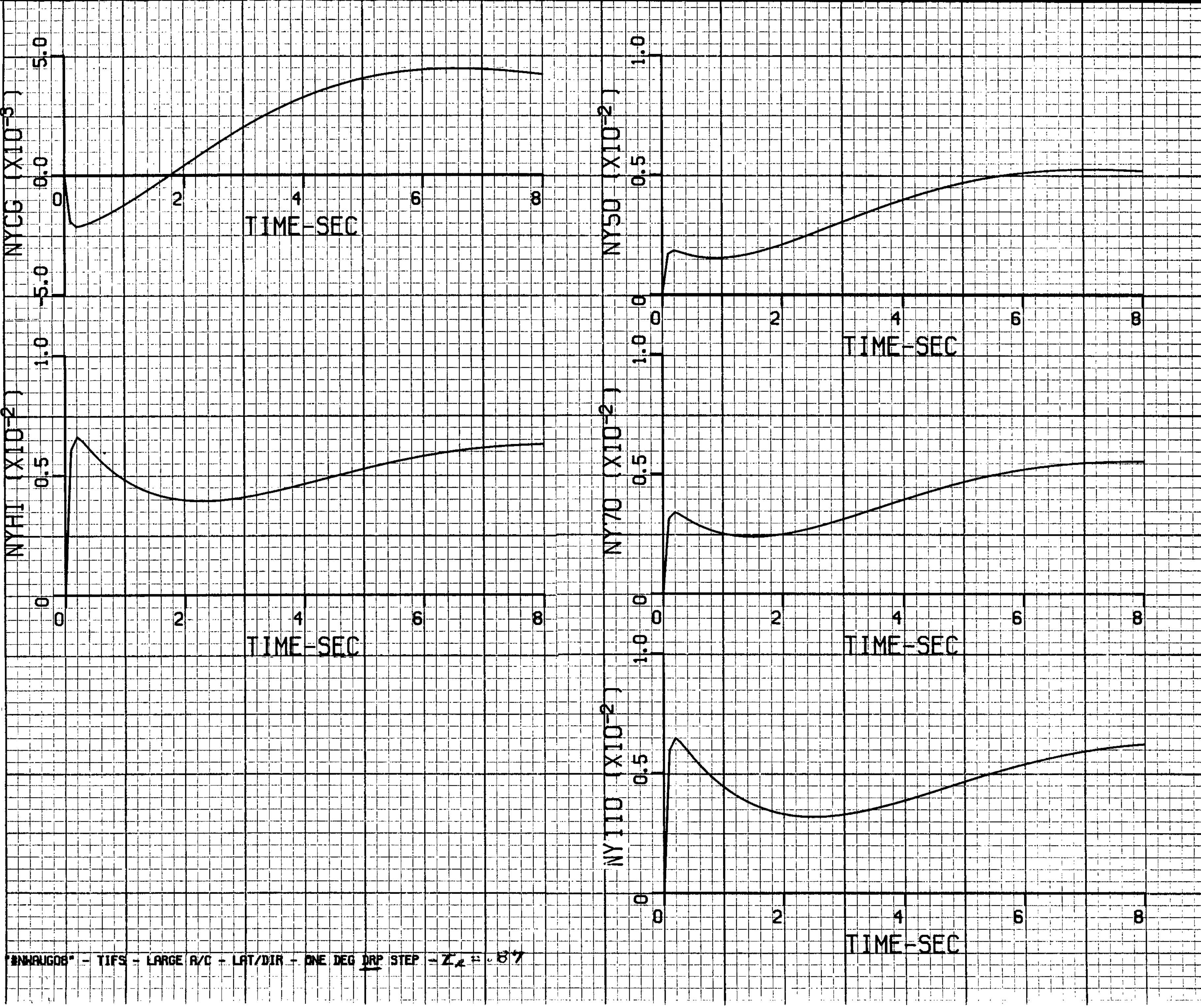


"*NHAUG08" - TIFS - LARGE A/C - LAT/DIR - ONE DEG DAW STEP - Z_R=.87


PHI (X10-1)
0.40
0.20
0
R* (X10-2)
0.40
0.20
0
P* (X10-3)
2
1
0
BETA (X10-2)
0
-1
-2
R (X10-2)
1.0
0.5
0
P (X10-2)
1.0
0.5
0
TIME-SEC
0
2
4
6
8
"*NWAUGO8" - TIFS - LARGE A/C - LAT/DIR - ONE DEG DRP STEP - ζ_{x} = .87



"BNWAUG08" - TIFS - LARGE A/C - LAT/DIR - ONE DEG DRP STEP - Z_{ℓ} = .87

Appendix III

PILOT COMMENT SUMMARIES

This appendix presents a brief summary of the important pilot comments for each Short Aft Tail configuration evaluation. A transcription of the complete pilot comments is available from Calspan files. Along with the pilot comment summaries are the full description of the configuration, pilot ratings, flight number/configuration order on flight, date, meteorological conditions, and airport.

Configurations are presented in the following order:

α-Feedback, q-Feedback
Low to High augmentation level
Time delay $T_1 = A, B, C$

SHORT AFT TAIL α AUGMENTATION — PILOT COMMENT SUMMARIES

Med α — $T_1 = A, B$

High α — $T_1 = A, B$

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT A
Short	α_{Med}	-10	A	4.2	--	.87	18	A	RATING 10
									PIO 5

FLT/CONF.	619/2	WIND	5-10 kt tailwind	VISIBILITY	Clear
DATE	8/4/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: Moderate to heavy.
- Displacement: Moderate.
- Sensitivity: About right.
- Trim: Didn't use trim.

PITCH ATTITUDE RESPONSE:

- Initial: Delayed and sluggish.
- Predictability: Fair in up and away and extremely difficult in flare and touchdown.
- Special Inputs: Not sure.
- PIO Tendency: Definite tendency to PIO in the last few feet before touchdown. It's a bad configuration, you think you have it set up pretty well and then you get into trouble.

AIRSPEED CONTROL: Somewhat difficult, seemed to bleed without giving me any awareness.

PERFORMANCE:

- Approach Tasks:
  - ILS: Glide slope was not operating. Localizer was reasonable. Airspeed demanding.
  - Visual (Sidestep): Sidestep went fine. Final part of approach seemed to go ponderously but O.K., but anytime you need a flight path correction close in, it just seemed to be extremely difficult to make.
- Landing Tasks: Flare and touchdown was extremely difficult, you tended to PIO.
- Differences: Extremely big difference - it just felt heavy in the approach whereas in the flare and touchdown, it was very imprecise and you oscillated when you tried to produce touchdown conditions. By far, the flare and touchdown was most difficult.

WIND AND TURBULENCE: Turbulence probably was a factor. Crosswind not a problem. Lat-Dir. was good.

SUMMARY COMMENTS: Major problem - was the flight path control in pitch in flare and touchdown. Get flight path PIO in last few feet.

TAIL	AUG.	$X_{P_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	B
Short	α_{Med}	-10	B	4.2	--	.87	18	A	RATING	10
									PIO	6

FLT/CONF.	615/4	WIND	Headwind	VISIBILITY	Clear
DATE	7/31/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: No complaints.
- Displacement: No complaints.
- Sensitivity: No complaints.

PITCH ATTITUDE RESPONSE:

- Initial: No real complaints when you are above 50 ft.
- Predictability: Poor, I did notice even on approach a little nibble of an oscillation on occasion. Oscillations were small on approach and controllable.
- Special Inputs: Tone down your inputs, not be aggressive.
- PIO Tendency: PIO Tendency, on approach very mild, in landing very severe.

AIRSPEED CONTROL: Satisfactory on approach. Lousy in flare.

PERFORMANCE:

- Approach Tasks:
  - ILS: Good.
  - Visual (Sidestep): Good down to 50 ft.
- Landing Tasks: Flare is major problem. I can't get the airplane organized below 50 ft.
  Some of the characteristics interfere with my ability to precisely control the approach to get in the window correctly.
- Differences: Landing was clearly the worst task.

WIND AND TURBULENCE: Turbulence was detracting factor Couldn't find a special technique that worked.

SUMMARY COMMENTS: Major problem. Lack of predictability in pitch and a great deal of difficulty in controlling and predicting the touchdown point and sink rate, mostly the sink rate, Down to 50 ft it is quite manageable. I could fly i rather precisely, under 50 ft I cannot get the airplane organized. Severe PIO in the flare.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
Short	α_{Med}	-10	B	4.2	--	.87	18	A	RATING	10
									PIO	5

FLT/CONF.	618/5	WIND	5-10 kt tailwind	VISIBILITY	Clear
DATE	8/4/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: Steady state the forces are medium but in PIO they get modertae to heavy.
- Displacement: Tend to get large in PIO.
- Sensitivity: Pretty good choice.

PITCH ATTITUDE RESPONSE:

- Initial: Delayed.
- Predictability: Very difficult.
- Special Inputs: Have to anticipate that it is going to be a delayed response. Make corrective inputs in opposition to nose rate. Compensation control is complex.
- PIO Tendency: Very definite tendency to PIO both IFR and VFR but it's very much worse VFR.

AIRSPEED CONTROL: Difficult.

PERFORMANCE:

- Approach Tasks:
  - ILS: High workload in pitch and tended to oscillate. Localizer not bad, not much time for it. Airspeed high workload.
  - Visual (Sidestep): Tend to forget about sidestep.
- Landing Tasks: It's bad in flare and touchdown. It's a PIO bugger. You can develop a technique that helped by keeping deviations small and putting in elevator inputs, pulse inputs in opposition to pitch rate. Very high workload.
- Differences: Flare and touchdown most difficult. Lat-Dir. characteristics are good.

WIND AND TURBULENCE: Turbulence is bothersome, takes long time to correct disturbances.

SUMMARY COMMENTS: Major problem - PIO in flare. Just a matter of time 'til you kill yourself in this one. PIO doesn't get divergent until flare.
Good feature - Lat-Dir.
Below 350 ft the PIO started, all I had to do was look at the ground and I was in a PIO.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	B
Short	α_{Hi}	-10	A	4.2	--	.87	18	A	RATING	10
									PIO	4

FLT/CONF.	615/3	WIND	Headwind	VISIBILITY	Clear
DATE	7/31/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: No complaints, little aft stick in turns.
- Displacement: No complaints.
- Sensitivity: No complaints.

PITCH ATTITUDE RESPONSE:

- Initial: Good, except right down near the ground.
- Predictability:
- Special Inputs:
- PIO Tendency:

AIRSPEED CONTROL: Reasonable until last 20 ft, unacceptable in last 20 ft.

PERFORMANCE:

- Approach Tasks:
  - ILS: No problem, you can fly perfect ILS in this airplane.
  - Visual (Sidestep): Everything O.K. down to 20-25 ft.
- Landing Tasks:
- Differences:

Flare and touchdown performance was very poor. Tried several control techniques. First, I flew in a normal fashion and that didn't work. I could really feel myself ballooning and getting into a position where I knew the next oscillation was going to be a crunch and there wasn't anything I could do about it. I knew that I was putting my wheels down harder as I pulled back. The second one I was high and ended up with high sink rate and long. I then tried to not make any big changes close in. So I'm going to come in and duck under just a little bit and come in low and make a change and hold it. I attempted to do that and came close to making it, but ended up at about 10 feet fresh out of peanuts and the next oscillation I knew we were in trouble, extended long and slow very significant difference between approach and landing. The most significant that I've seen. You could not believe that you would have as much trouble as you do under 25 ft.

WIND AND TURBULENCE: Wind and turbulence not a factor. Lat-Dir. not a factor.

SUMMARY COMMENTS: Major problems were precise control of sink rate close to the ground and Lord knows what was happening to the landing gear back there as we were floundering around in the oscillation. I don't feel like I was losing control in a sense of pitch oscillation, but I was certainly losing control of my sink rate so that's what I mean. You don't feel like it's losing control of pitch attitude directly, but clearly got into oscillations when I attempted to enter the loop under 25 ft.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
									RATING	9
Short	α_{Hi}	-10	A	4.2	--	.87	18	A	PIO	5

FLT/CONF.	618/4	WIND	5-10 kt tailwind	VISIBILITY	Clear
DATE	8/4/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: Medium to a little heavy.
- Displacement: Large.
- Sensitivity: O.K..
- Trim: Didn't trim too much.

PITCH ATTITUDE RESPONSE:

- Initial: Noticeably delayed.
- Predictability:
- Special Inputs:
- PIO Tendency:

Predictability of pitch is not bad IFR and also VFR when you are up and away from the ground but as soon as the ground comes in you really definitely can perceive the altitude errors and it screws you up and starts a PIO going. I think it is an input I'm putting in to correct the altitude errors that causes the PIO.

AIRSPEED CONTROL: Wasn't really bad. Surprisingly.

PERFORMANCE:

- Approach Tasks:
  - ILS: Can't remember too clear. Localizer was good. Airspeed wasn't bad.
  - Visual (Sidestep): Sidestep was easy.
- Landing Tasks: Problems came in the flare and touchdown because of PIO in pitch and it was very, very hard to stabilize the flight path close to the ground. Kind of reminds me of the shuttle.
- Differences:

WIND AND TURBULENCE: Didn't particularly notice turbulence. May have been setting off PIO because I did detect an altitude error that was growing and I didn't seem to be able to control it. My efforts to control it seemed to drive me into the PIO. Lat-Dir. was O.K..

SUMMARY COMMENTS: Major problem - The PIO in flare and touchdown. As you start tight control in the flare, it causes an oscillation that is divergent.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT A
Short	α_{Hi}	-10	A	4.2	--	.87	18	A	RATING 8
									PIO 4

FLT/CONF.	630/2	WIND	Headwind	VISIBILITY	Partly cludy & slightly hazy.
DATE	8/13/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: Heavy. Steady elevator required in steady turn.
- Displacement: Large.
- Sensitivity: I increased it initially and considered further increase but decided against it. Might increase PIO tendency.
- Trim: I guess I didn't trim, but I sure got airspeed variations.

PITCH ATTITUDE RESPONSE:

- Initial: Very sluggish and delayed.
- Predictability: Poor.
- Special Inputs: Either overdrive it, which tends to result in overcontrol or to just nudge it around, don't overdrive it.
- PIO Tendency: Definite tendency to PIO.

AIRSPEED CONTROL: Poor. Always behind it and trying to correct. The inaccuracy in pitch control is a significant part of problem

PERFORMANCE:

- Approach Tasks:
  - ILS: Poor until I got steady down then fair. Localizer degraded because of lack of attention. Airspeed was poor. Altitude control extremely difficult.
  - Visual (Sidestep): Sidestep went O.K. laterally but got off in vertical flight path.
- Landing Tasks: Flare and touchdown performance was very variable. If you are right on, it came out fairly decently. But if you're off and try to correct back, it was just hopeless. The pilot-airplane combination for any sizeable correction is very poor dynamically, very slow and very oscillatory.
- Differences: Both approach and landing were difficult. It was the landing that's going to kill you though.

WIND AND TURBULENCE: Turbulence is distracting. Lat-Dir. was good.

SUMMARY COMMENTS: Major problem is the slow, inadequate pitch response, difficulty in predicting what to put in to get what you want. Tend to overdrive it or to shift to a mode where you just kind of nudge it around, in which case you don't have the desired bandwidth in generating airplane responses.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
Short	$^{\alpha}Hi_{DLC}$	-10	A	4.2	--	.87	18	A	RATING	6
									PIO	3

FLT/CONF.	630/3	WIND	Headwind	VISIBILITY	Partly cloudy & slightly hazy.
DATE	8/13/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: Elevator forces on the heavy side, but not too heavy.
- Displacement: Medium.
- Sensitivity: Little low, but about right. Had to put nose down elevator trim in on final a couple of times. Don't understand that.

PITCH ATTITUDE RESPONSE:

- Initial: Very slow initial response, ponderous.
- Predictability: Poor.
- Special Inputs: Either don't put much in and sit there and wait or try to overdrive it, but not too much.
- PIO Tendency: Definite tendency to PIO in pitch on flight path control close to ground.

AIRSPEED CONTROL: Difficult and high workload, but you can do it.

PERFORMANCE:

- Approach Tasks:
  - ILS: Glide slope and localizer not too bad except got high and fast close in. Airspeed was a problem, high workload.
  - Visual (Sidestep): Sidestep easy but the vertical flight path was difficult to control and tended to get off.
- Landing Tasks: Flare and touchdown - I tried to control attitude. The best combination was to control attitude and do most of the flare with the elevator but not worrying about the tight control of sink rate, then control the sink rate with the DLC. That worked pretty well in the last two landings but I didn't have force feel on my DLC controller. DLC controller is not the best predictor type device, I tended to overdo it, maybe if I had force feel -- I don't really know but anyway it's not optimized. That technique tends to work but it's high workload because you have elevator and aileron to control with your left hand and airspeed plus DLC with the right hand so you're busy.
- Differences: The most difficult to control is the flare and touchdown, but flight path and airspeed on final during turns was also a problem. Lat-Dir. is best part of this configuration.

WIND AND TURBULENCE: Crosswind correction was easy.

SUMMARY COMMENTS: Major problem - High workload but I was able to stay out of trouble with the configuration by using the DLC, wereas, I would have gotten into a significant PIO in trying to flare. I felt slow and ponderous and difficult close to the ground as far as elevator control went. Good features - The DLC gave me a tighter control of the sink rate near touchdown and especially, I want this noted, to be able to start back down if I had overrotated with my elevator in pitch. To be able to start down promptly is highly desirable feature of the DLC - and then being able to take out that down correction quickly. It's very helpful. It makes it possible to come down a little without rotating, I'd never have gotten it done if I had to rotate the airplane.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
									RATING	10
Short	α_{Hi}	-10	B	4.2	--	.87	18	A	PIO	6

FLT/CONF.	619/1	WIND	5-10 kt tailwind	VISIBILITY	Clear
DATE	8/4/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: Heavy on first approach, arm got tired. Increased gain by about 1.43 and then forces were moderate.
- Displacement: Large.
- Sensitivity: Too heavy on initial approach. Increase by 1.43.
- Trim: Didn't use trim.

PITCH ATTITUDE RESPONSE:

- Initial: Delayed.
- Predictability: Unpredictable.
- Special Inputs: Not too special IFR. VFR you try to perform flare and touchdown you get divergent PIO.
- PIO Tendency:

AIRSPEED CONTROL: Taxiing, lots of attention.

PERFORMANCE:

- Approach Tasks:
  - ILS: Not bad at all. Airspeed was little poor.
  - Visual (Sidestep): Sidestep easy.
- Landing Tasks: Flare and touchdown - go into PIO and it was just hopeless. Tried three landings and couldn't do it. Safety pilot took control.
- Differences: Landing is more difficult, it's divergent PIO.

WIND AND TURBULENCE: Turbulence was submerged in other problems. Lat-Dir. only good thing.

SUMMARY COMMENTS: Major problem - PIO in flare and touchdown. It was divergent. I couldn't land it in three attempts. Everything proceeded normally until I got down to about 200 ft and then it fell out of the sky on the flare and I went into a PIO, overrotate, balloon, overrotate down, etc..

SHORT AFT TAIL q AUGMENTATION — PILOT COMMENT SUMMARIES

Med q	—	$T_1 = A$
High q ($X_{PCR} = -10'$)	—	$T_1 = A$, *Shuttle lag/delay*
High q ($X_{PCR} = 10'$)	—	$T_1 = A$
High q	—	$T_1 = A$
Ex-High q	—	$T_1 = A$

TAIL	AUG.	$X_{P_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
Short	q_{med}	-10	A	4.2	1.0	.87	18	A	RATING	9
									PIO	4

FLT/CONF.	619/3	WIND	5-10 kt tailwind	VISIBILITY	Clear
DATE	8/4/80	TURB.	Light	AIRPORT	Rochester

FEEL:

- Forces: Medium
- Displacement: Large
- Sensitivity: Asked that be increased after first approach.
- Trim: Didn't use trim.

PITCH ATTITUDE RESPONSE:

- Initial: Very sluggish and delayed.
- Predictability: Difficult to predict.
- Special Inputs: Stay on top of it all the time. In flare you had to generate a lot of corrective lead type inputs to nurse the response towards what you want.
- PIO Tendency: Very strong PIO tendency but it can be made convergent.

AIRSPEED CONTROL: Poor primarily because I didn't have time to give it much attention.

PERFORMANCE:

- Approach Tasks:
  - ILS: Glide slope was fair. Localizer reasonably good. Airspeed had excursions.
  - Visual (Sidestep): Sidestep easy.
- Landing Tasks: Flare and touchdown was a problem, had a tendency to overrotate. PIO, whenever you wanted to make a correction in flight path. Just don't know what kind of an input to put in.
- Differences: Approach was a lot less difficult than landing.

WIND AND TURBULENCE: It is turbulent today which makes it hard to ever really get set up.
Lat-Dir good.

SUMMARY COMMENTS: Major problem is pitch PIO in flare and touchdown. Difficult to predict what kind of input to put in to get the flight path response you want.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT B
Short	q_{Hi}	-10	A	4.2	1.0	.87	18	A	RATING 6 PIO 3

FLT/CONF.	615/5	WIND	Headwind	VISIBILITY	Clear
DATE	7/31/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: No problem.
- Displacement: No problem.
- Sensitivity: O.K.

PITCH ATTITUDE RESPONSE:

- Initial: Pitch response was excellent. Certainly at all times except the very last approach, even then I was able to retain a reasonable control. Initial response was good.
- Predictability: Predictability was good.
- Special Inputs: Not to make inputs near the ground.
- PIO Tendency: If you use the wrong technique. It's related to technique you use.

AIRSPEED CONTROL: Good on first and reasonable on the second.

PERFORMANCE:

- Approach Tasks:
  - ILS: You can do excellent ILS. It's an excellent airplane.
  - Visual (Sidestep): Good visually down to last bit but you got to get organized there. You have to get set up so you come through the window correctly and then almost hands off technique close in. Use the trim to make inputs.
- Landing Tasks: Flare and touchdown was the problem. Performance was both good and bad. It's very much a function of control technique.
- Differences: Difference is significant and landing is clearly the most difficult.

WIND AND TURBULENCE: Wind and turbulence was not a factor. Lat-Dir was not a factor.

SUMMARY COMMENTS: Major problem is precision of height control near the ground. I'd like to see it again, didn't get consistent results.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
Short	q_{Hi}	-10	A	4.2	1.0	.87	18	A	RATING	9
									PIO	4

FLT/CONF.	619/4	WIND	5-10 tailwind	VISIBILITY	Clear
DATE	8/4/80	TURB.	Light	AIRPORT	Rochester

FEEL:

- Forces: Medium or a little heavier. No steady forces in the turn.
- Displacement: Medium or a little larger.
- Sensitivity: About right but the feel is terrible, it just --- you don't feel like you are too connected to the airplane.

PITCH ATTITUDE RESPONSE:

- Initial: Delayed.
- Predictability: Not at all good, but adequate for IFR portion. It's no way near adequate for flare and touchdown.
- Special Inputs: Had not developed one.
- PIO Tendency: Definite tendency to PIO.

AIRSPEED CONTROL: Difficult in the approach. You were so busy in the flare that airspeed control was not existent.

PERFORMANCE:

- Approach Tasks:
  - ILS: Fair but workload was high. Arispeed control was a problem also rate of climb. Localizer didn't seem to correct as well as others. Performance was certainly adequate.
  - Visual (Sidestep): Sidestep was not difficult.
- Landing Tasks: The flare is the problem, especially down close to touchdown. Tended to overrotate. Flight path just doesn't want to go that last 6 inches or one foot. I ended up with the flight path going up and then it's hard to correct, end up with another shot back down on the runway with sink rate that is too large.
- Differences: By far the landing was the most difficult.

WIND AND TURBULENCE: Turbulence was a problem, it knocks you off the glide slope and it's very difficult to get back on. Lat-Dir pretty good.

SUMMARY COMMENTS: Major problems was flare and touchdown. I'm tired having crappy airplanes in the flare and touchdown. If you can't build them any better than this, we better not build them.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
Short	q_{Hi}	-10	A	4.2	1.0	.87	18	A	RATING	5
									PIO	3

FLT/CONF.	630/1	WIND	6 kt headwind	VISIBILITY	Partly cloudy & Slightly hazy
DATE	8/13/80	TURB.	Light turbulence	AIRPORT	Niagara

FEEL:

- Forces: Heavy initially, medium after I increased the gearing. No force required for turn.
- Displacement: Large initially, medium after gain increase.
- Sensitivity: Prefer the higher setting.
- Trim: Didn't use trim, didn't have to.

PITCH ATTITUDE RESPONSE:

- Initial: Little delayed and sluggish.
- Predictability: Little hard to predict final but adequate.
- Special Inputs: I was probably overdriving it some.
- PIO Tendency: I hate to call it a PIO but it certainly had some overcontrol tendency in flare and touchdown, which appeared as an oscillation.

AIRSPEED CONTROL: Fair, required attention.

PERFORMANCE:

- Approach Tasks:
  - ILS: Somewhat busy, had airspeed variations. Glide slope attention took some attention off localizer. Airspeed, noticeable workload.
  - Visual (Sidestep): Sidestep was easy. Didn't have much trouble with vertical flight path.
- Landing Tasks: Flare - I was a little behind, but I had control.
- Differences: Approach and landing similar difficulty with a little more trouble with the touchdown.

WIND AND TURBULENCE: Turbulence added to airspeed corrections. Lat-Dir. pleasant but a little heavy.

SUMMARY COMMENTS: No major problems but the airplane is slow, sluggish responding in pitch. But I do have adequate control. Didn't get desired performance in airspeed or flight path control in the flare and touchdown. Tendency to be late in the flare, ponderous and a little hunting for the ground in pitch.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT B
Short	q_{Hi}	-10	A	4.2	1.0	.87	18	A	RATING 4
									PIO 2

FLT/CONF. 631/5	WIND 12 kt headwind	VISIBILITY Light rain and hazy
DATE 8/14/80	TURB. Moderate	AIRPORT Buffalo

FEEL:
- Forces: Reasonable.
- Displacement: Reasonable.
- Sensitivity: Reasonable.

PITCH ATTITUDE RESPONSE:
- Initial: Slow.
- Predictability: No problem.
- Special Inputs: No.
- PIO Tendency: No.

AIRSPEED CONTROL: O.K..

PERFORMANCE:
- Approach Tasks:
  - ILS: Satisfactory.
  - Visual (Sidestep): Satisfactory.
- Landing Tasks: Flare - used more gradual throttle changes and it seemed to work out better. I had more trouble with the directional and lateral correction in that particular landing than anything else. I was unable to really get set up for it. I don't think it's a fair offset for a large airplane - I would have gone around.
- Differences: No significant difference between approach and landing.

WIND AND TURBULENCE: The crosswind seemed larger than usual, I had both hands on the wheel and a lot of rudder, more than I've been used to.

SUMMARY COMMENTS: No major problems. I thought it was a little slow in pitch, a little tendency to be less precise than you want. Had a little tendency to overcontrol in the flare but wasn't set up very good.

TAIL	AUG.	$X_{P_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT	A
Short	$q_{Hi_{DLC}}$	-10	A	4.2	1.0	.87	18	A	RATING	5
									PIO	3 elev. 2 DLC
FLT/CONF.	629/3		WIND	15 kt headwind			VISIBILITY		Partly cloudy	
DATE	8/12/80		TURB.	Moderate			AIRPORT		Niagara	

(See Detail Comments for DLC experience)

FEEL:

- Forces: Medium
- Displacement: Medium
- Sensitivity: Probably should have tried it a little higher.

PITCH ATTITUDE RESPONSE:

- Initial: Delayed.
- Predictability: Not quite so good with elevator.
- Special Inputs: Overdrive a little maybe.
- PIO Tendency: None on glide slope but some in the flare and touchdown with elevator.

AIRSPEED CONTROL: Requires a lot of thrust in turns.

PERFORMANCE:

- Approach Tasks:
  - ILS: Fairly good. Didn't use DLC in approach.
  - Visual (Sidestep): Sidestep easily done in roll but some tendency to lose the flight path in vertical.
- Landing Tasks: Flare - If done with the elevator, the response is delayed and some tendency to oscillate, tendency to overrotate. Touchdown performance, only did one with elevator and that one wasn't too bad.
- Differences: The landing is more difficult than the approach. Flare and touchdown with the DLC, it is only used on flight path but it is difficult to know how much change in h that you are commanding. I just moved the thumb control and see what happens. After a few landings, I was doing it about right.

WIND AND TURBULENCE: Crosswind corrections were O.K.. Some tendency to neglect the crosswind when using DLC.

SUMMARY COMMENTS: Major problem is four controls, I was learning and it is probably a help but I'm not sure that's the kind of help I want. Workload is high with four controllers. I'm still learning to use DLC and the controller isn't optimized. Sense of control was O.K., never used it backwards.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT A RATING 5 PIO 1
Short	q_{Hi}	+10	A	4.2	1.0	.87	18	A	

FLT/CONF.	629/1	WIND	260^o @ 15 kt	VISIBILITY	Partly cloudy
DATE	8/12/80	TURB.	Moderate	AIRPORT	Buffalo

FEEL:

- Forces: Medium
- Displacement: Small to medium
- Sensitivity: Liked the value I had.
- Trim: Didn't have to trim.

PITCH ATTITUDE RESPONSE:

- Initial: Delayed a little but didn't seem to give me any significant problem in the flare and touch n.
- Predictability: Seemed predictable. I didn't overrotate.
- Special Inputs: None.
- PIO Tendency: None.

AIRSPEED CONTROL: Principal problem was airspeed control. Wasn't bad when I was wings level constant speed flight but if I would be turning or rolling out of the turn or in response, it had a tendency to get slow or fast. Sluggish thrust response.

PERFORMANCE:

- Approach Tasks:
  - ILS: Quite good ILS and localizer. Turning, I had little trouble with airspeed.
  - Visual (Sidestep): Easy to correct and no problem with vertical flight path during the maneuver.
- Landing Tasks: I landed a little early and hard on first two but I think the problem is primarily getting used to Buffalo airport and the radar altitude for this runway. (Sharp change in elevation near threshold). Third landing, the sink rate was kept small without overrotation. No special technique, except watch airspeed.
- Differences: Approach was more difficult because of airspeed control.

WIND AND TURBULENCE: Not sure what the effect of turbulence was. Crosswind easy. Lat-Dir was good.

SUMMARY COMMENTS: Principal problem was airspeed control, did not get desired performance. Good features - Lat-Dir and in a sense the pitch control and the flare and touchdown wasn't bad.

TAIL	AUG.	$X_{P_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT B
Short	q_{Hi}	10	A	4.2	1.0	.87	18	A	RATING 8 land. 4 appr. PIO 3 flare

FLT/CONF.	631/1	WIND	SW @ 12 kt	VISIBILITY	Light rain and slightly hazy
DATE	8/14/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: No complaints.
- Displacement: No complaints.
- Sensitivity: Satisfactory.
- Trim: I really didn't like the airplane even in the approach. It didn't seem to trim in an attitude and hold it, I had to be trimming all the time. Wasn't a solid airplane on approach.

PITCH ATTITUDE RESPONSE:

- Initial: Little bit delayed. I didn't have a great deal of difficulty, didn't feel smooth, a little lumpy.
- Predictability:
- Special Inputs:
- PIO Tendency: No tendency toward a PIO except right near the end. Tend not to want to touch it, lack of controllability you would like to see in the flare.

AIRSPEED CONTROL: Reasonable, required work but could get job done.

PERFORMANCE:

- Approach Tasks:
  - ILS: No problem on ILS, throttles are used open loop, you move the throttle and wait an hour until it settles down.
  - Visual (Sidestep): No difference from IFR.
- Landing Tasks:
- Differences:

The real differences is in flare and touchdown. The problems are an inability to fly in a natural fashion and be precise with a touchdown point without feeling that you are going to overcontrol and hit the ground too hard and fall out the bottom like I did on the secon one. The clear problem is the landing, it's significant right near the end. Lot of mental workload to keep from overcontrolling and getting into a balloon situatio in touchdown. You can hit the ground pretty hard in this airplane.

WIND AND TURBULENCE: Wind and turbulence not really a factor. Crosswind no problem. Lat-Dir. not a factor.

SUMMARY COMMENTS: Major problem is the last 30-40 ft in the landing. I just have a feeling that I am not totally in control of the rate of sink at touchdown, or the touchdown point. Worry about hitting ground too hard. Second landing contributes to this fear. On approach it is something like a 4.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT A
Short	q_{Hi}	50	A	4.2	1.0	.87	18	A	RATING 4-1/2 PIO 1

FLT/CONF.	629/2	WIND	260° @ 15 kt	VISIBILITY	Partly cloudy
DATE	8/10/80	TURB.	Moderate	AIRPORT	Buffalo

FEEL:
- Forces: Medium and comfortable.
- Displacement: Medium to small.
- Sensitivity: Didn't do any trimming.

PITCH ATTITUDE RESPONSE:
- Initial: Prompt for a big airplane.
- Predictability: Pretty predictable.
- Special Inputs: None.
- PIO Tendency: None.

AIRSPEED CONTROL: Bit of a problem.

PERFORMANCE:
- Approach Tasks:
  - ILS: Very tood. Airspeed on ILS was fair.
  - Visual (Sidestep): Sidestep was easy.
- Landing Tasks: No particular problem in flare.
- Differences: Approach was more difficult, I had to watch the airspeed a lot and had problems with speed in the flare.

WIND AND TURBULENCE: Crosswind corrections were easy, took turbulence in stride. Lat-Dir were good.

SUMMARY COMMENTS: Major problem was airspeed control and thrust lag. Don't know where to put the throttle to get the trim thrust back. Have to look at throttle and guess where to put it. Didn't get desired performance in airspeed. On last approach turning final, I let the airspeed get down to 142 kt and with full power on, nothing much happened, gradually started to pick up.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT B
Short	q_{Hi}	50	A	4.2	1.0	.87	18	A	RATING 3
									PIO 1

FLT/CONF.	631/4	WIND	SW @ 12 kt	VISIBILITY	Light rain and slightly hazy.
DATE	8/14/80	TURB.	Moderate	AIRPORT	Niagara

FEEL:

- Forces: No problem.
- Displacement: No problem.
- Sensitivity: Satisfactory.

PITCH ATTITUDE RESPONSE:

- Initial: Good.
- Predictability: Predictable.
- Special Inputs: None.
- PIO Tendency: None.

AIRSPEED CONTROL:

PERFORMANCE:

- Approach Tasks:
  - ILS: Didn't achieve the performance on first two approaches that I expected. There was some confusion of the first couple. Concentrated a little more on third one and you can do the job.
  - Visual (Sidestep): Can do.
- Landing Tasks: Felt I had reasonable control of sink rate and touchdown point.
- Differences: No real difference between approach and landing. Final flare was a little more difficult.

WIND AND TURBULENCE: Felt turbulence in ride quality sense, not in terms of control problem. Crosswind correction required seemed to change as got closer to ground, maybe variable wind.

SUMMARY COMMENTS: No major problems. Good features - sense of control near the ground, I could control the sink rate in satisfactory manner. I must admit that knowing the kind of airplane (short tail) that I'm flying and of course not knowing what on earth is going on with them - there is a tendency to want to say, well, I should be having more difficulty --- a reluctance to give full marks for precision.

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT B
Short	q_{Hi}	-10	Shuttle lag/delay	4.2	1.0	.87	18	A	RATING 9 PIO 5

FLT/CONF.	631/2	WIND	SW @ 12 kt	VISIBILITY	Light rain and slightly hazy
DATE	8/14/80	TURB.	Light	AIRPORT	Niagara

FEEL:

- Forces: O.K..
- Displacement: O.K..
- Sensitivity: Satisfactory.
- Trim: Has PIO tendency if you hand fly it at any time on an accurate attitude. You can fly with the trim most of the approach, but near the end if you are trying to make a correction, it's very difficult to avoid a PIO.

PITCH ATTITUDE RESPONSE:

- Initial: Big initial delay.
- Predictability: Poor.
- Special Inputs: Use trim as much as possible; not make any inputs.
- PIO Tendency: PIO anytime you try to be accurate with the airplane.

AIRSPEED CONTROL: Reasonable.

PERFORMANCE:

- Approach Tasks:
  - ILS: Using trim, could achieve adequate ILS.
  - Visual (Sidestep): Sidestep can be done, rather not have to though. You would like to be stabilized far out on final and not have to touch anything.
- Landing Tasks: Flare and touchdown is clear problem area. Special technique is to try to stay out of loop. It's a very tense airplane to fly near the end because you're worried that you are going to touch it at the wrong time and get into an oscillation.
- Differences: Tendency to PIO and landing is most difficult.

WIND AND TURBULENCE: Wind and turbulence no problem. Lat-Dir. not a factor.

SUMMARY COMMENTS: Major problem - lack of predictability in the pitch response combined with a difficult airplane to feel a sense of control of sink rate near the end of the flare. Can't consistently land it with acceptable sink rate. Inability to make corrections in the flare.

Note: ↓

TAIL	AUG.	$X_{p_{C.R.}}$	$t_1 \sim q$	n/α	T_q	τ_R	$-Z_{sp}$	$\tau_1 \sim p$	PILOT B
Short	q_{ExHi}	-10	A	4.2	0.5	.87	18	A	RATING 4
									PIO 2

FLT/CONF.	631/3	WIND	SW @ 12 kt	VISIBILITY	Light rain and slightly hazy.
DATE	8/14/80	TURB.	Moderate	AIRPORT	Niagara

FEEL:

- Forces: No complaints.
- Displacement: No complaints.
- Sensitivity: Satisfactory.
- Trim: Decent airplane to trim.

PITCH ATTITUDE RESPONSE:

- Initial: O.K..
- Predictability: Good.
- Special Inputs: Could fly the airplane and not feel apprehension and muscle tightening worry about getting into trouble.
- PIO Tendency: None.

AIRSPEED CONTROL: What you want to make it. Satisfactory. I found I was actually relaxing in this airplane compared to some. In relaxing you tend to get a little sloppy.

PERFORMANCE:

- Approach Tasks:
  - ILS: No problem.
  - Visual (Sidestep): No problem.
- Landing Tasks: I may be learning to fly these things. I seem to have a lot more confidence with this airplane that I could put it down where I wanted it. Felt like I had to work just a little bit at the end, a little sense of caution, but I kept things under control.
- Differences: Landing clearly more difficult than approach.

WIND AND TURBULENCE: Didn't notice turbulence problems, but crosswind seemed stronger than before. The correction takes time, it's slow coming around. Have to get organized as you would in a big airplane, allow a reasonable distance, you can get it done.

SUMMARY COMMENTS: Major problem - none. I felt a sense of relief being able to fly the airplane close to the ground without PIO. I felt a little apprehension at the end and a little work. I feel comfortable with this airplane but I don't feel like I'm achieving the performance that I expect.

Appendix IV

OPEN-LOOP AIRCRAFT PLUS COMPENSATED PILOT NICHOLS DIAGRAMS, $\theta/\theta_\varepsilon$

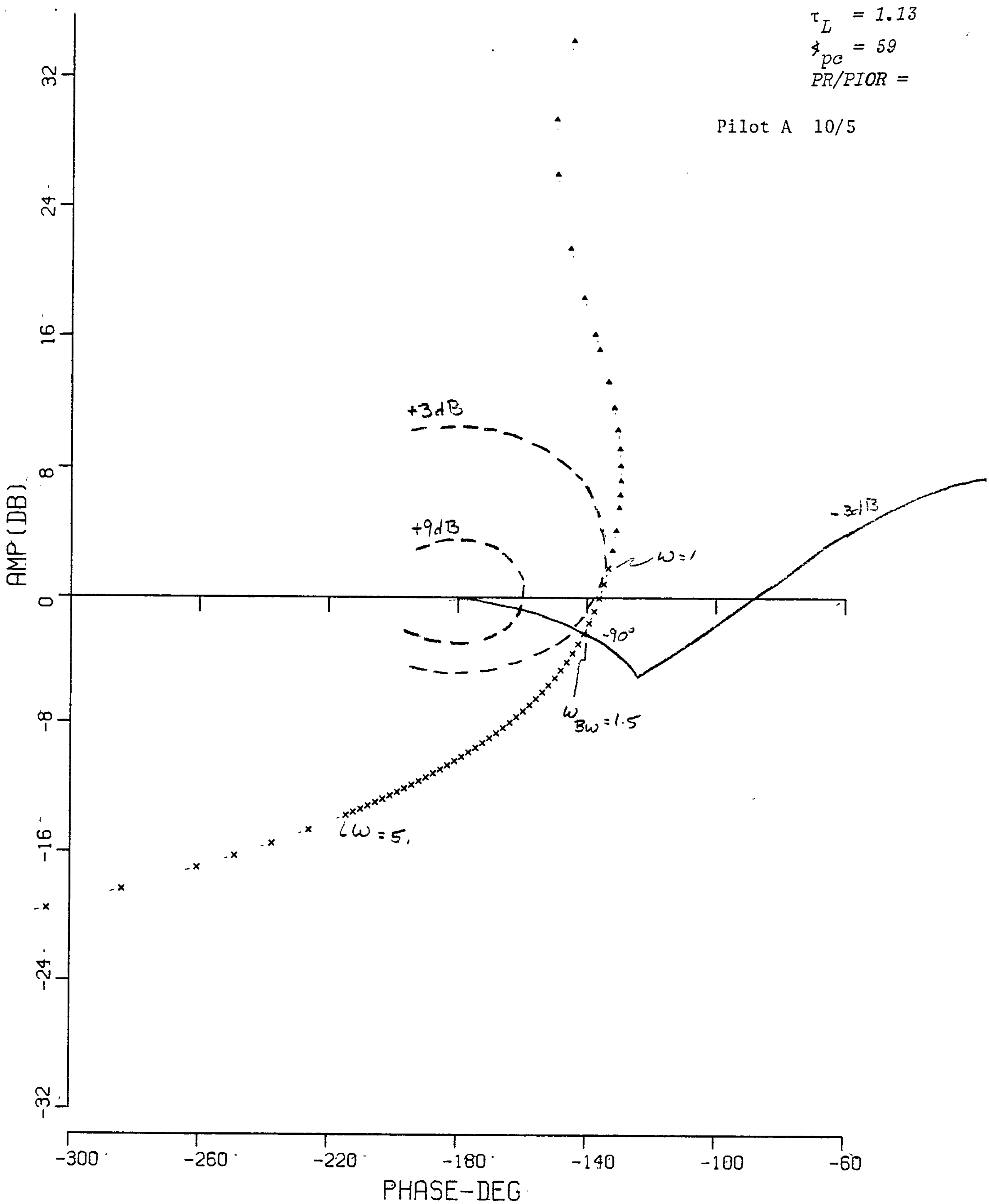
This appendix presents the open-loop aircraft plus compensated pilot Nichols diagrams for each Short Aft Tail configuration evaluated. The pilot model contains a .25 second delay and low-frequency integration capability $\left(\frac{5s+1}{s}\right)$. The gain ($K_{p_\theta}$) and lead compensation ($\tau_L s+1$) was adjusted to achieve a closed-loop bandwidth (ω_{BW_θ}) of 1.5 rad/sec without violating the closed-loop droop and resonance boundaries. The solution requiring minimum pilot lead was selected in most cases. The pilot compensation is discussed in Section 4.3.2.

$$\theta/\theta_\varepsilon = K_{P_\theta} \; (\tau_L s+1) e^{-.25s} \left(\frac{5s+1}{s}\right) \theta/F_{ES}$$

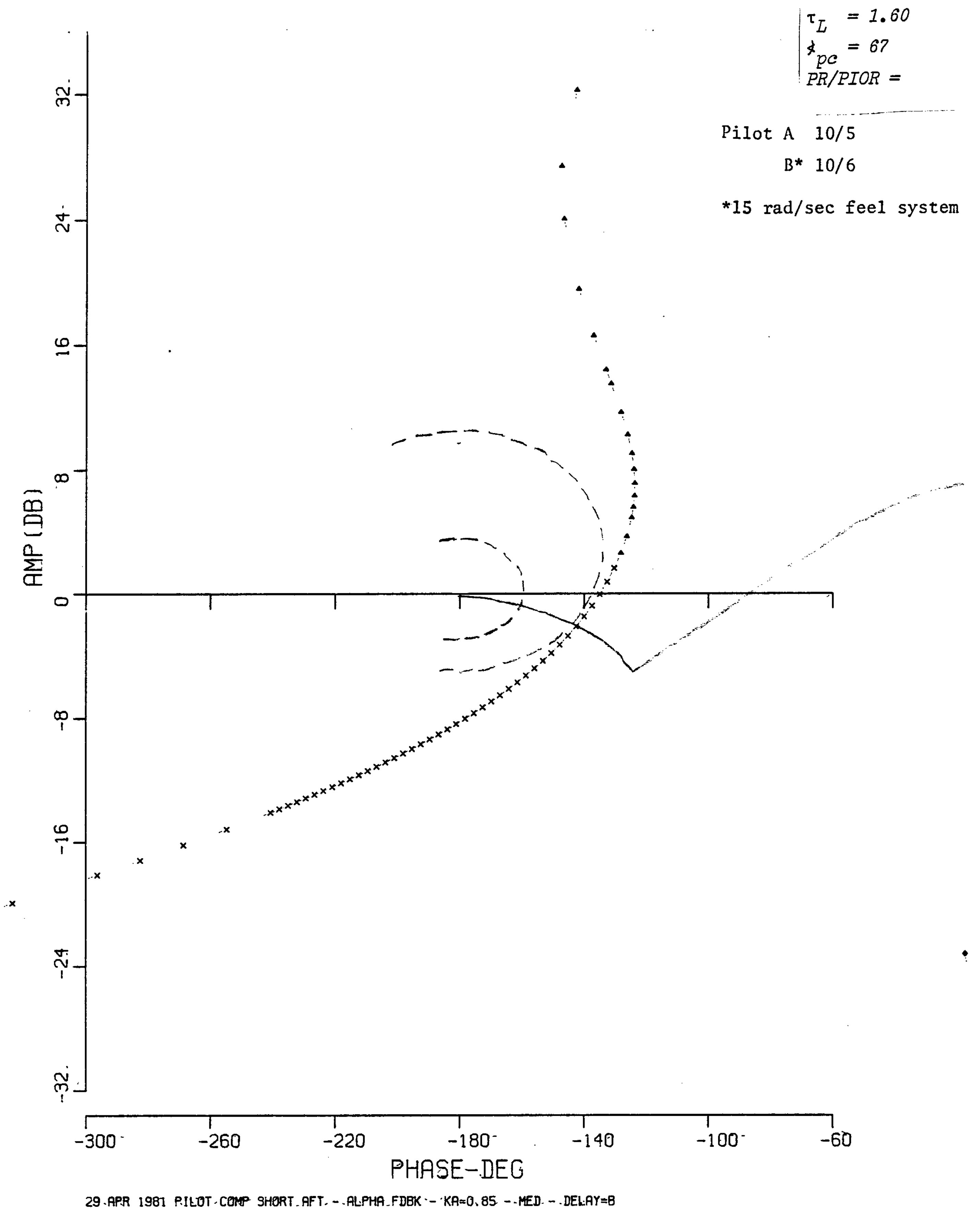
The closed-loop analysis was performed using the 25 rad/sec feel system for all configurations. The caption on each plot defines the configuration. Also drawn on each plot are the closed-loop +3 dB, +9 dB resonance; -3 dB droop, and -90 degrees phase lines. The 1.5 rad/sec point passes through the -90 degree phase line indicating the closed-loop bandwidth. Listed on each plot is the lead time constant used, phase compensation at ω_{BW} and pilot rating/PIO rating received. The order of the frequency points is:

(rad/sec) ▲ = .1, .12, .14, .16, .2, .24, .28, .3, .35, .4, .45, .5, .55, .6, .65, .7, .8, .9

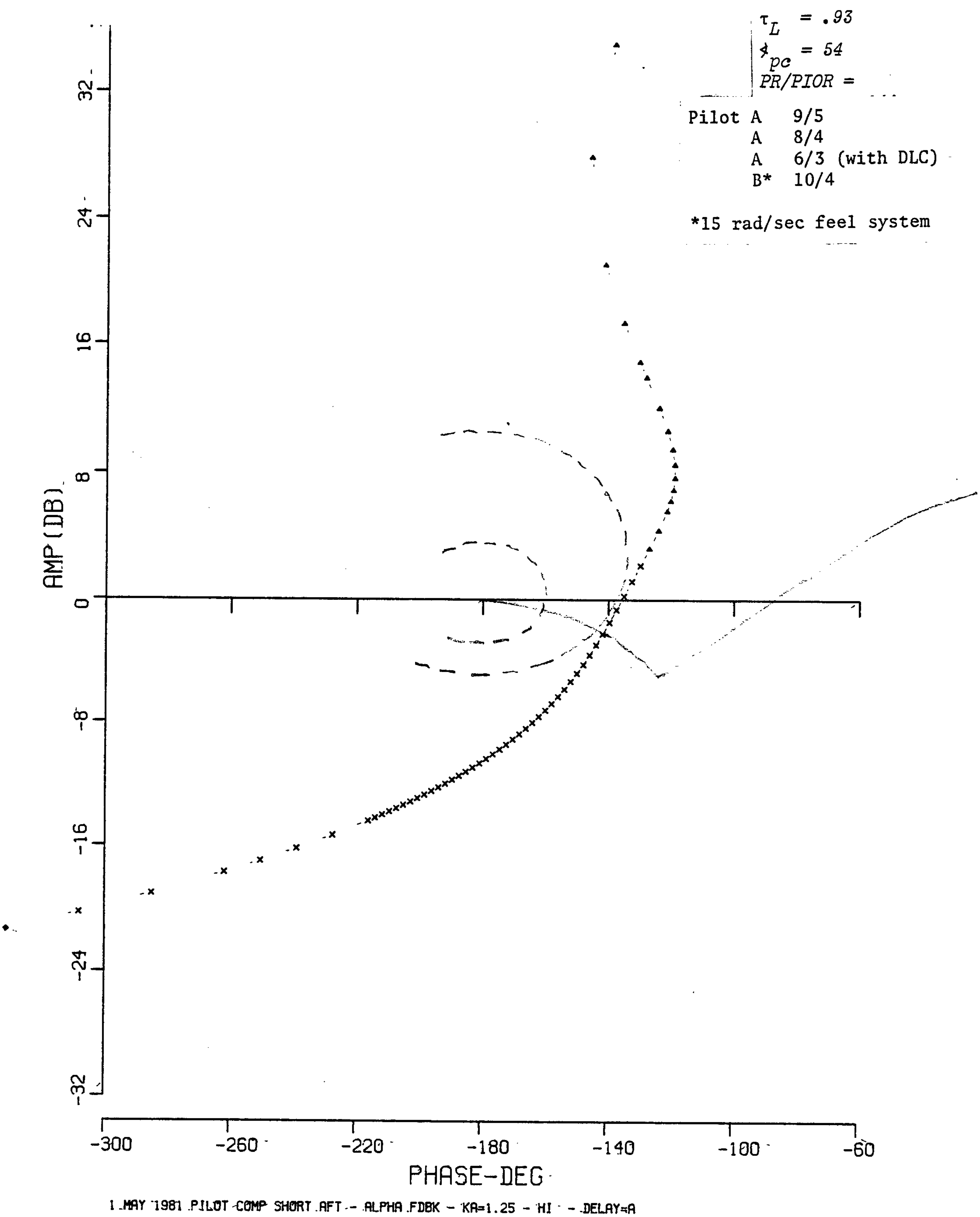
X = 1., 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2., 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3., 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 4., 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 5., 5.5, 6., 6.5, 7., 8., 9., 10.



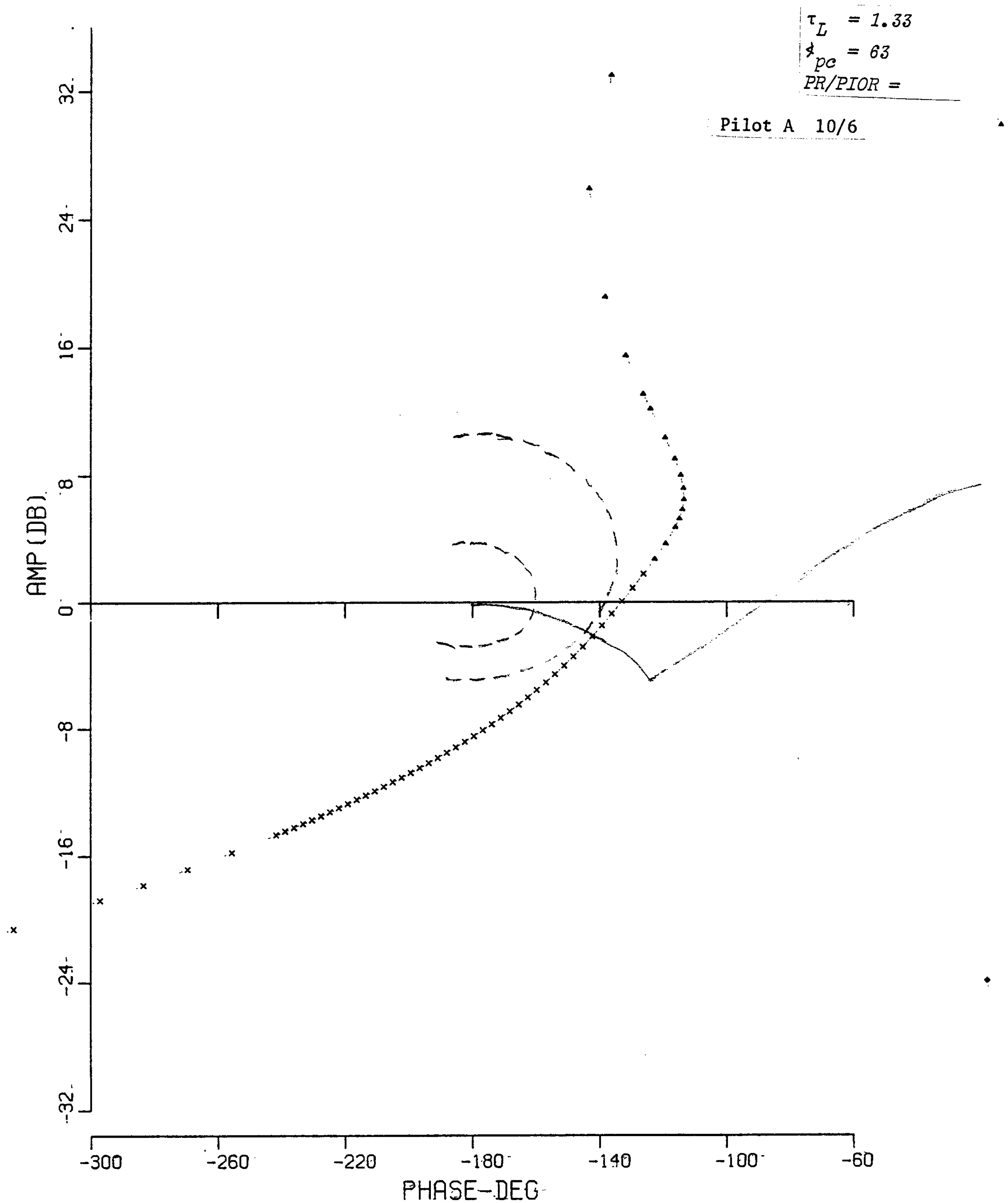
1 MAY 1981 PILOT COMP SHORT AFT - ALPHA FDBK - KA=0.85 - MED - DELAY=A



τ_L = 1.60
$\measuredangle_{pc}$ = 67
PR/PIOR =
Pilot A 10/5
B* 10/6
*15 rad/sec feel system
32
24
16
8
0
-8
-16
-24
-32
AMP (DB)
-300
-260
-220
-180
-140
-100
-60
PHASE-DEG
29 APR 1981 PILOT COMP SHORT AFT - ALPHA FDBK - KA=0.85 - MED - DELAY=B



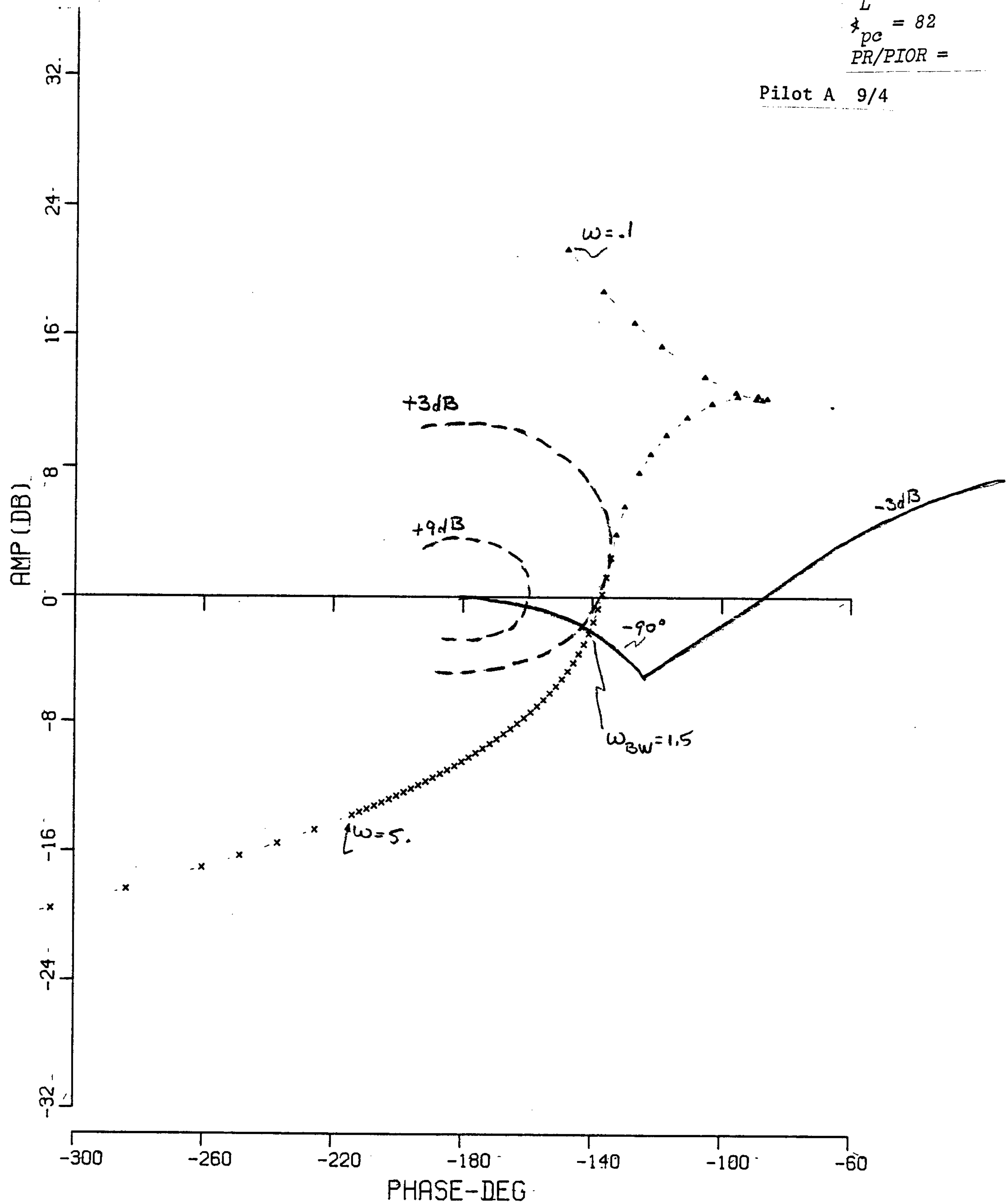
τ_L = .93
$\measuredangle_{pc}$ = 54
PR/PIOR =
Pilot A 9/5
A 8/4
A 6/3 (with DLC)
B* 10/4
*15 rad/sec feel system
AMP (DB)
32
24
16
8
0
-8
-16
-24
-32
-300
-260
-220
-180
-140
-100
-60
PHASE-DEG
1 MAY 1981 PILOT COMP SHORT AFT - ALPHA FDBK - KA=1.25 - HI - DELAY=A



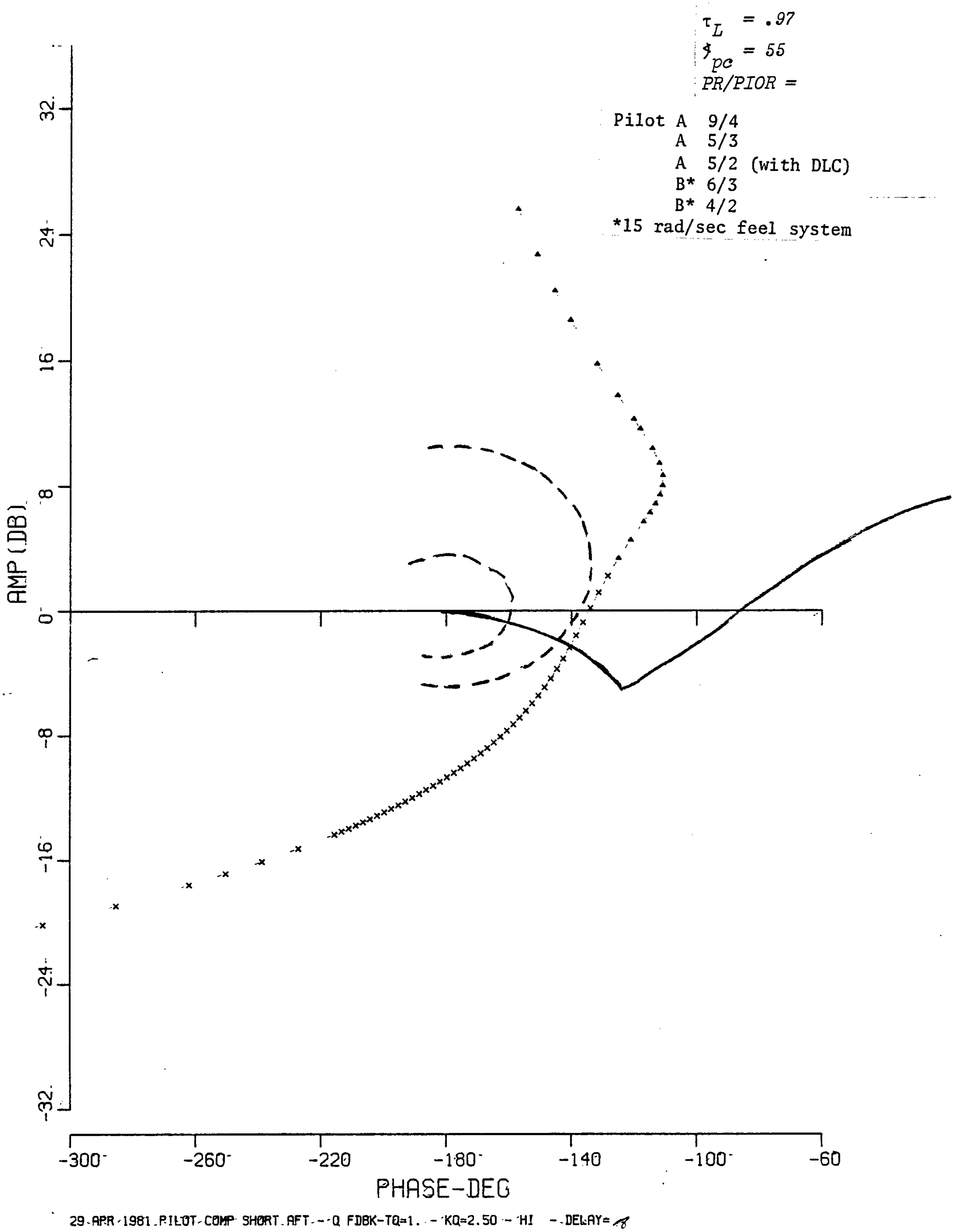
29 APR 1981 PILOT COMP SHORT AFT — ALPHA FDBK — KA=1.25 — HI — DELAY=8

τ_L = 4.67
ϕ_{pc} = 82
PR/PIOR =

Pilot A 9/4



1 MAY 1981 PILOT COMP SHORT AFT - Q FDBK-TQ=1. - KQ=1.05 - MED - DELAY= A

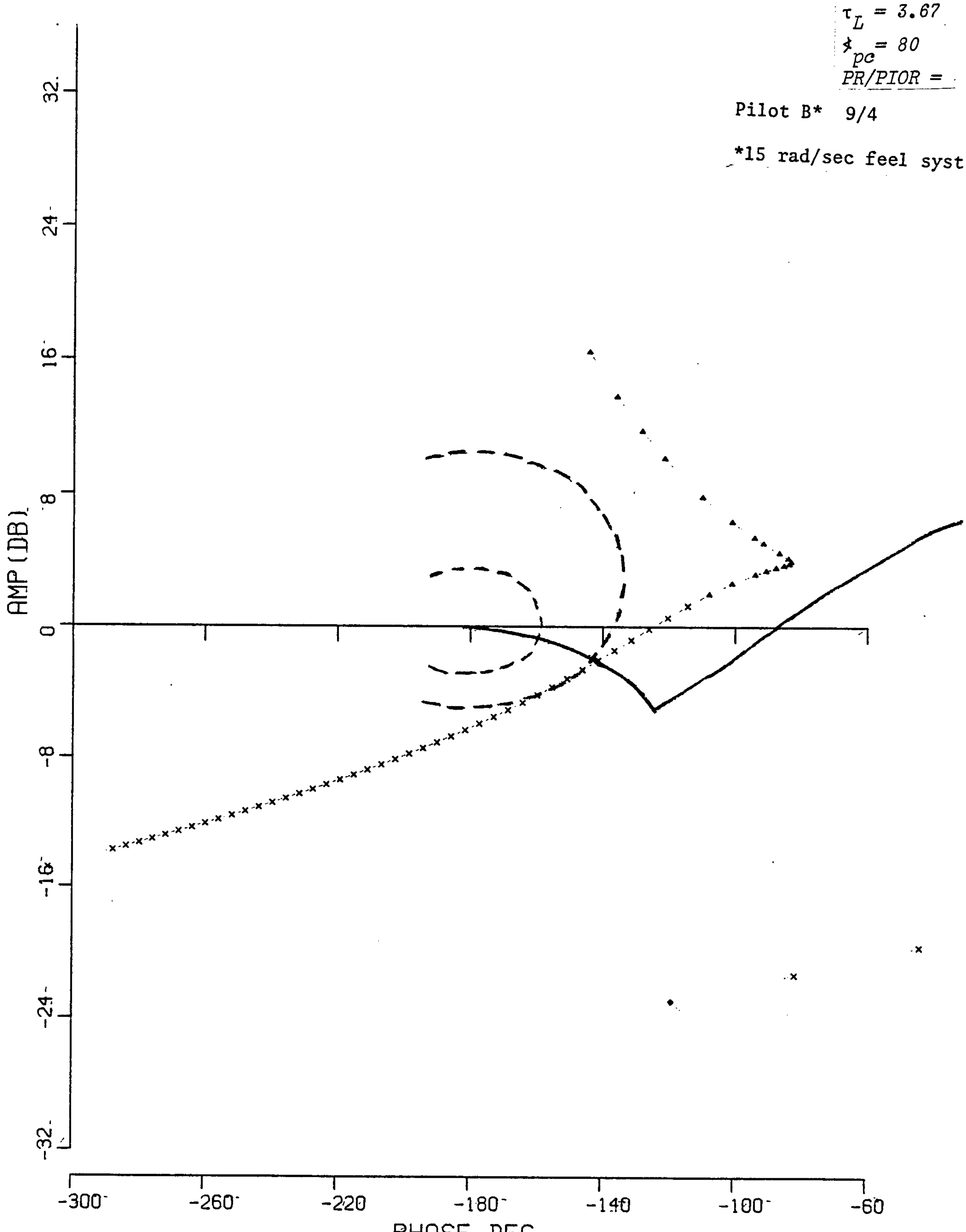


τ_L = .97
ζ_{pc} = 55
PR/PIOR =
Pilot A 9/4
A 5/3
A 5/2 (with DLC)
B* 6/3
B* 4/2
*15 rad/sec feel system
AMP (DB)
32.
24
16
8
0
-8
-16
-24
-32
-300
-260
-220
-180
-140
-100
-60
PHASE-DEG
29 APR 1981 PILOT-COMP SHORT AFT - Q FDBK-TQ=1. - KQ=2.50 - HI - DELAY=

$\tau_L = 3.67$
$\measuredangle_{pc} = 80$
PR/PIOR =

Pilot B* 9/4

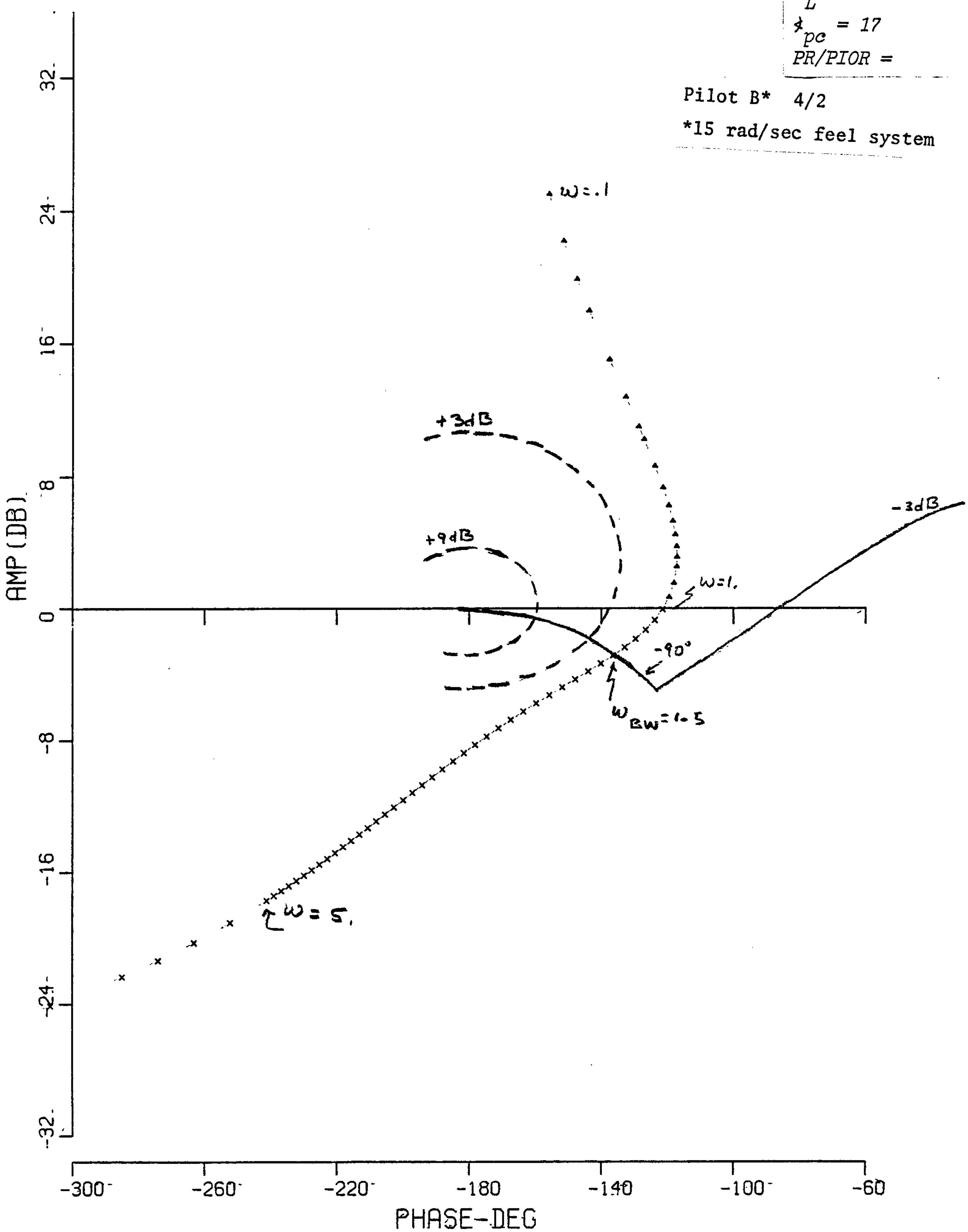
*15 rad/sec feel system



29 APR 1981 PILOT COMP SHORT AFT - - Q FDBK-TQ=1. - KQ=2.50 - HI - DELAY= .35

τ_L = .21
$\measuredangle_{pc}$ = 17
PR/PIOR =

Pilot B* 4/2
*15 rad/sec feel system



29 APR 1981 PILOT COMP SHORT AFT - - Q FDBK-TQ=.5 - KQ=5.2 - - EX-HI - - DELAY = A

Appendix V
ADDITIONAL ANALYSIS RESULTS

This Appendix presents the results of additional analyses which were conducted:

Appendix V-A — Equivalent System Analysis
V-B — Time History Criteria for Pitch Rate Response
V-C — Open-Loop (Aircraft Only) Pitch Attitude Analysis
V-D — Open-Loop (Aircraft Plus Uncompensated Pilot) Pitch Attitude Analysis

None of the criteria which were evaluated correlated very well with the data. All of the criteria show the correct general trend of good ratings tending toward the good area of each criteria plot and bad ratings tending towards the Level 3 directions of parameter values. As mentioned in the body of this report, there are effects in the data that are not handled by the criteria. These are pilot location relative to center of rotation, backside operation and slow thrust response, and benefits and shortcomings of the augmentation systems. Some of these latter effects are gust sensitivity, low frequency and phugoid dynamics, elevator forces required in turns, backside and slow thrust response more critical for α-augmentation, and low q-augmentation is detrimental versus low α-augmentation.

Appendix V-A
EQUIVALENT SYSTEM ANALYSIS

Equivalent lower order systems were generated for each of the configurations by the Flight Dynamics Laboratory of the Air Force Wright Aeronautical Laboratories. The pitch rate to stick force transfer function was matched with a first order numerator plus an equivalent time delay, over a second-order denominator. The lower order system match is of the form:

$$\frac{q}{F_{ES}} = \frac{K\left(s + \frac{1}{T_{\theta_e}}\right)e^{-T_D s}}{s^2+2\zeta_e\omega_{sp_e}s+\omega_{sp_e}^2}$$

The match was done from .25 r/s to 10 r/s for 25 equally spaced frequency values on a log scale. The matching algorithm uses a cost function of

$$\text{COST} = \frac{20}{n}\sum_{\omega_1}^{\omega_n} \left[(gain_{HOS} - gain_{LOS})^2 + .01745\ (phase_{HOS} - phase_{LOS})^2\right]$$

where

ω denotes the input frequency gain is in dB

Phase in degrees

n is the number of frequencies.

The computer program did not require using an unstable root in any of the low order system matches for any of the configurations even though some of the configurations had an unstable root.

The pure time delay effects of .06 seconds for the TIFS model-following or any intentionally introduced pure time delay (.07 records for $T_{1_{pitch}} = C$) would add directly to the equivalent time delay shown in the low order system matches.

The following is an explanation of the table of equivalent system parameters (Table V-A-1) for the Short Aft Tail configuration.

The symbol P in the CONF (configuration) column signifies the first order command prefilter $\left(\frac{1}{.111s+1}\right)$ was included in the higher order system model.

K = numerator coefficient (NUM. COEFF.)

$\frac{1}{T_{\theta_e}}$ = equivalent numerator zero, fixed at the true value of L_α or $\frac{1}{T_{\theta_2}}$ or allowed to run free, $\frac{1}{\text{sec}}$.

T_D = equivalent time delay $\left(\begin{array}{c}\text{EQUIV}\\ \text{TIME DELAY}\end{array}\right)$, sec.

(This does not include any pure time delay effects such as the TIFS model-following delay of .06 seconds or any intentionally introduced pure time delay).

ζ_e = equivalent damping ratio

ω_{sp_e} = equivalent short period natural frequency, rad/sec

The upward pointing arrows beside some of the $\frac{1}{T_{\theta_e}}$ free values mean that when the program was stopped, the value of $\frac{1}{T_{\theta_e}}$ was still being raised by the program (usually after about 2500 iterations). In all cases, the fit was excellent as shown by the relatively low value of the COST function.

For $n_z/\alpha = 2$ for the long aft tail configuration, the pitch rate numerator did not reduce to two real roots, but instead, was two complex roots; so only $\frac{1}{T_{\theta_e}}$ free could be matched for this configuration.

The equivalent time delay matches for the 25 r/s feel system, the 15 r/s feel system, and a 20 r/s first-order actuator are:

25 r/s feel = .058 sec time delay, COST = .02

15 r/s feel = .100 sec time delay, COST = .75

20 r/s actuator = .048 sec time delay, COST = 1.75

Inspection of many of the configurations without the command prefilter (which adds about .09 seconds of equivalent time delay when included) shows that the equivalent time delay for these configurations is essentially due to the feel system and actuator dynamics.

When two negative numbers are listed vertically in the ζ_e-ω_{sp_e} columns, the equivalent system denominator for these configurations factored to two real roots at the values shown.

A comparison of the equivalent system parameters ω_{sp_e} and τ_{delay} to MIL-F-8785C criteria for short period frequency requirements and allowable response delay for the Short Aft Tail configurations are shown in Figure V-A-1, along with the pilot ratings received. Only points obtained with $\frac{1}{T_{\theta_e}}$ fixed are presented.

The flying quality levels for equivalent time delay and short period frequency are combined in Figure V-A-2, where the pilot ratings for the configurations flown are called out.

TABLE V-A-1. EQUIVALENT SYSTEM PARAMETERS

	CONF.	NUM. COEFF.	$\frac{1}{T_{\theta_e}}$	FIXED?	EQUIV. TIME DELAY *	ζ_e	ω_{sp_ε}	COST
			SHORT AFT TAIL α-FEEDBACK 25 R/S FEEL					
Unaug	$K_\alpha=0$	.1068	.5158	Y	.103	- .03607 - .9061		5.18
Unaug	$K_\alpha=0$	.1094	.8069	N	.106	- .06391 -1.301		3.44
Unaug	$K_\alpha=0P$	.09322	.5158	Y	.191	- .06339 - .7434		17.96
Unaug	$K_\alpha=0P$	.09332	.5411	N	.191	- .06601 - .7719		17.94
Med	$K_\alpha=.85$	.1117	.5158	Y	.104	.949	.578	1.92
Med	$K_\alpha=.85$	.08747	12.29†	N	.087	- .6632 -9.050		.65
Med	$K_\alpha=.85P$	.09761	.5158	Y	.191	.843	.563	21.76
Med	$K_\alpha=.85P$	.02174	38.00	N	.114	- .6666 -6.924		.82
High	$K_\alpha=1.25$	.1134	.5158	Y	.104	.826	.705	4.69
High	$K_\alpha=1.25$	.1093	1.205	N	.100	.808	1.020	2.81
High	$K_\alpha=1.25P$	.09901	.5158	Y	.192	.740	.682	26.6
High	$K_\alpha=1.25P$	.05039	11.58	N	.136	-1.089 -3.939		7.01

*Does not include model-following time delays.

TABLE V-A-1. EQUIVALENT SYSTEM PARAMETERS (CONT'D)

CONF.		NUM. COEFF.	$\frac{1}{T_{\theta_e}}$	FIXED?	EQUIV. TIME DELAY*	ζ_e	ω_{sp_e}	COST
		SHORT AFT TAIL q-FEEDBACK, $T_q = 1$, 25 R/S FEEL						
Med	K_q=1.05	.05808	.5156	Y	.104	.442	.499	1.84
	K_q=1.05	.05798	.5275	N	.104	.444	.502	1.82
	K_q=1.05P	.05242	.5156	Y	.195	.396	.493	20.73
	K_q=1.05P	.05070	.7174	N	.191	.434	.537	17.27
High	K_q=2.5	.1430	.5157	Y	.105	.713	.773	.98
	K_q=2.5	.1431	.5093	N	.105	.714	.770	.98
	K_q=2.5P	.1250	.5157	Y	.192	.639	.746	17.10
	K_q=2.5P	.1199	.9327	N	.186	.623	.929	14.52
Ex-Hi T_q=.5	K_q=5.2	.3695	.5158	Y	.124	.936	1.32	17.30
	K_q=5.2	.3126	1.927	N	.105	.618	2.17	1.09

*Does not include model-following time delays.

TABLE V-A-1. EQUIVALENT SYSTEM PARAMETERS (CONT'D)

(The following configurations were flown by Pilot B with 15 r/s pitch, feel system)

CONF.		NUM. COEFF.	$\frac{1}{T_{\theta_e}}$	FIXED?	EQUIV. TIME DELAY *	ζ_e	ω_{sp_ε}	COST
			SHORT AFT TAIL α-FEEDBACK, 15 R/S FEEL					
Med	K_α=.85P	.09674	.5158	Y	.233	.836	.563	27.22
	K_α=.85P	.008055	100.5↑	N	.139	- .6733 -6.755		1.56
High	K_α=1.25	.1124	.5158	Y	.146	.819	.705	6.86
	K_α=1.25	.1075	1.338	N	.141	.811	1.066	4.61
			SHORT AFT TAIL, q-FEEDBACK, T_q = 1, 15 R/S FEEL					
High	K_q=2.5	.1417	.5157	Y	.146	.708	.773	2.54
	K_q=2.5	.1417	.5169	N	.146	.708	.773	2.54
	K_q=2.5P	.1239	.5157	Y	.234	.634	.746	22.20
	K_q=2.5P	.1183	.9858	N	.228	.621	.947	19.30
Ex-Hi T_q=.5	K_q=5.2	.3647	.5158	Y	.166	.927	1.315	20.53
	K_q=5.2	.3032	2.093	N	.145	.605	2.227	2.58

*Does not include model-following time delays.

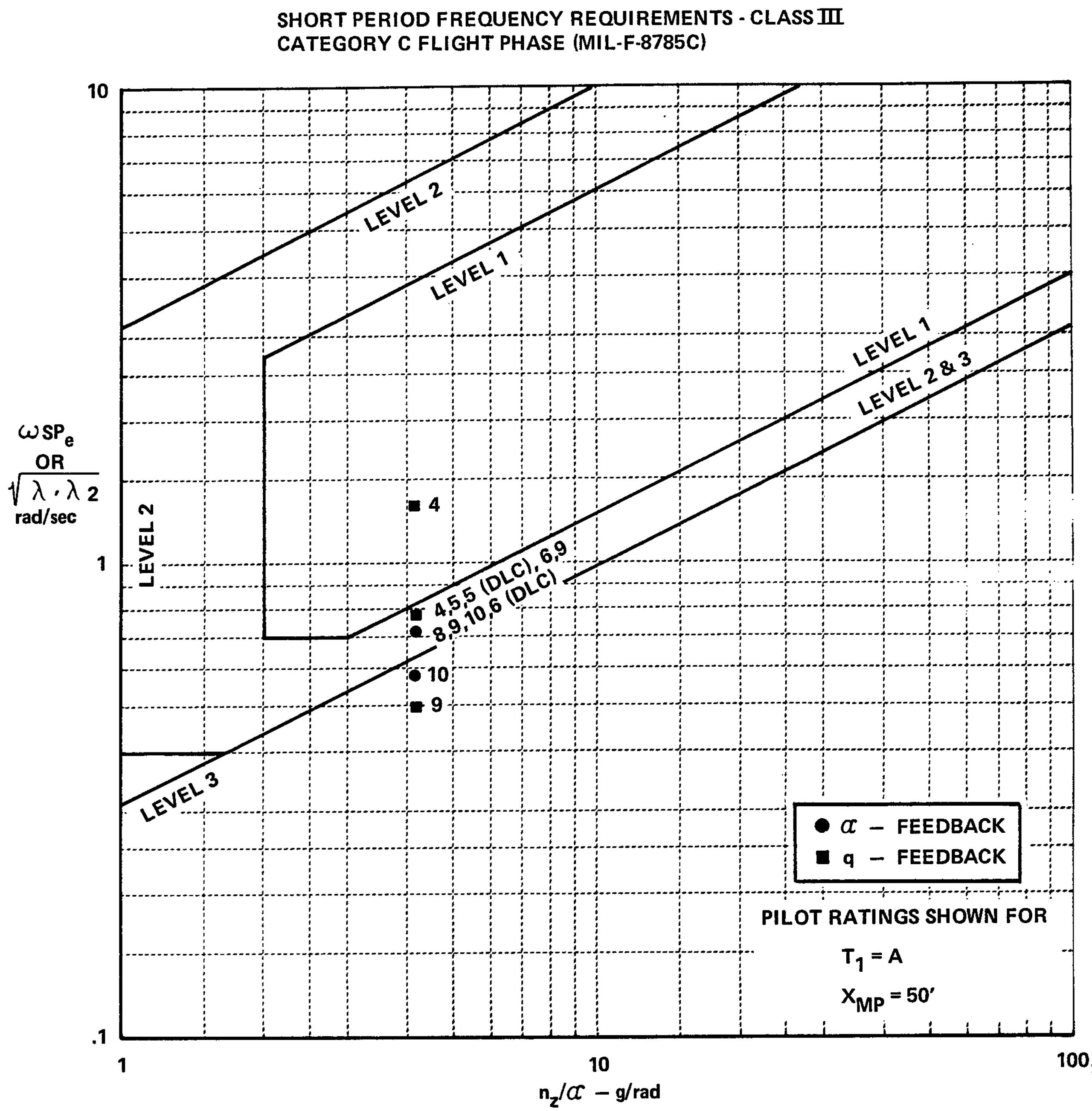


Figure V-A-1. SHORT AFT TAIL CONFIGURATIONS VS ω_{SP} REQUIREMENTS

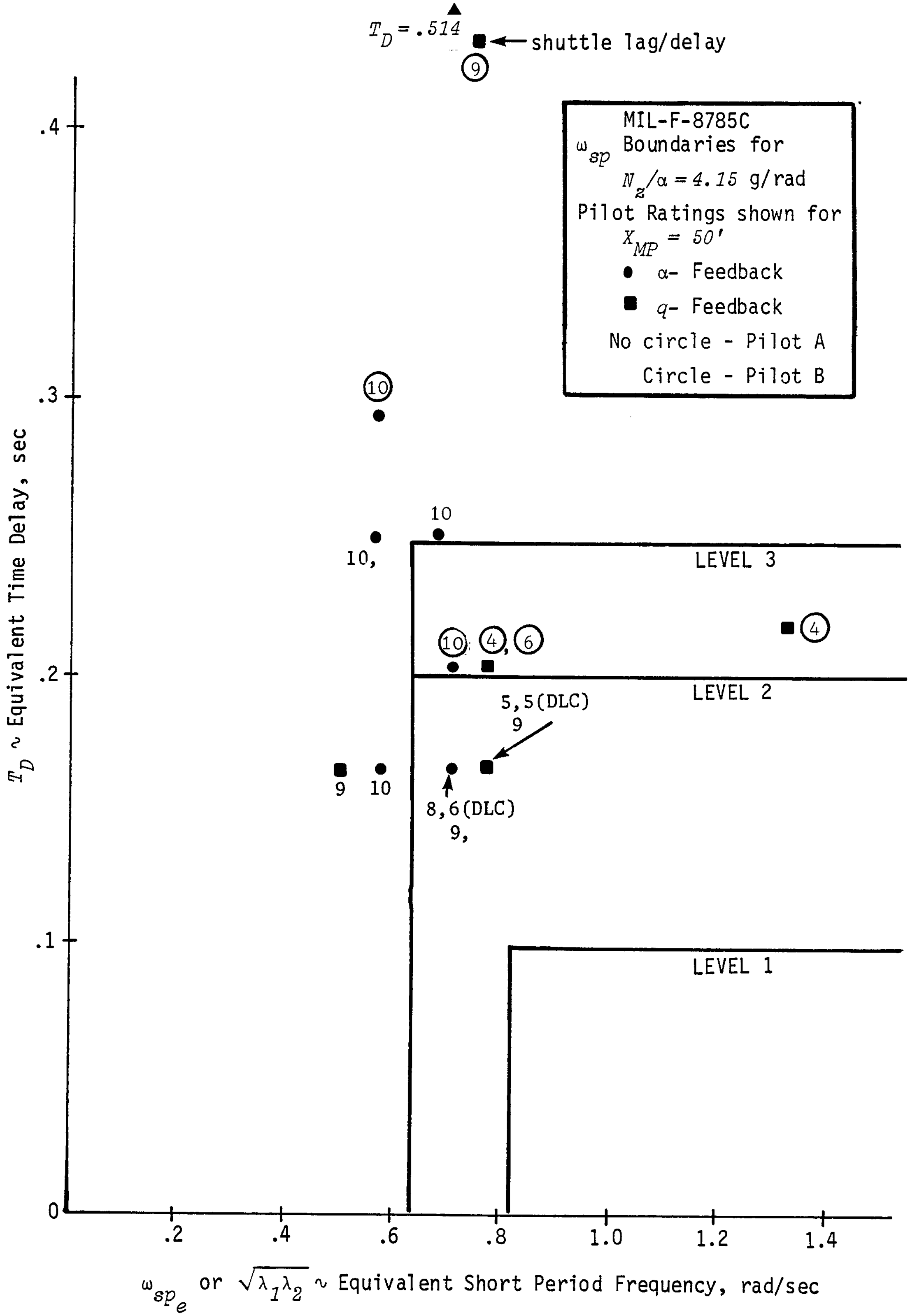


Figure V-A-2. SHORT AFT TAIL CONFIGURATIONS VS ALLOWABLE TIME DELAY

Appendix V-B

TIME HISTORY CRITERIA FOR PITCH RATE RESPONSE

The time history criteria for pitch rate response was developed in Reference 4 to correlate easily obtained parameters from a time history with flying qualities levels. It avoids identification of dominant roots or equivalent system models by working directly with the pitch rate transient response. To obtain the parameters for this criteria, the pitch rate response to a step input of pitch controller force is calculated from two degree-of-freedom equations of motion (i.e., with speed constrained). The response should exhibit the characteristics defined below. Two straight lines are drawn on the pitch rate time history and the following measurements are defined. See Figure V-B-1.

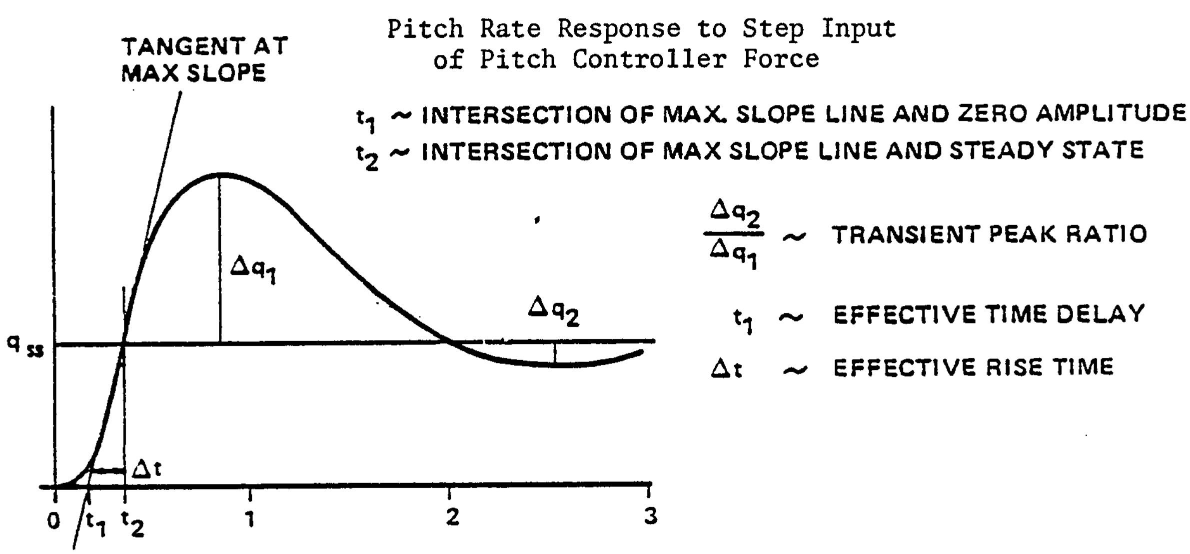


Figure V-B-1. TIME HISTORY CRITERIA PARAMETERS

a) A horizontal line defining the steady state pitch rate.

b) A sloping straight line tangent to the pitch rate time history at the point of maximum slope. This line is extended to intersect the steady state line and the time axis (maximum slope intercept).

c) Time t_1 is measured from the instant of the step input to the time corresponding to the intersection of the maximum slope line with the time axis.

d) Time t_2 is measured from the instant of the step input to the time corresponding to the intersection of the maximum slope line with the steady state line.

e) The amplitude quantities Δq_1 and Δq_2 are measured as follows: $\Delta q_1 \equiv$ maximum pitch rate minus the steady state; $\Delta q_2 \equiv$ the steady state minus the first minimum.

The above defined measurements shall meet the following design criteria.

<u>Effective Time Delay</u>

The time t_1 is considered an equivalent time delay and shall be within the limits specified below.

t_1 ~ effective time delay in command path

Level	Pitch
1	.12 sec
2	.17 sec
3	.21 sec

These time delay values are nominal values found tolerable for demanding control tasks (such as landing) in combination with good airplane dynamics. Significantly smaller command path time delays may be required to realize acceptable flying qualities in specific cases. Conversely, significantly larger values may be tolerable in less demanding tasks.

Transient Peak Ratio

The transient peak ratio $\Delta q_2/\Delta q_1$ shall be equal to or less than the following:

Level	$\Delta q_2/\Delta q_1$
1	.30
2	.60
3	.85

Rise Time Parameter

The parameter $\Delta t = t_2 - t_1$ shall have a value between the following limits:

	Nonterminal Flight Phases	Terminal Flight Phases
Level	Min Δt Max	Min Δt Max
1	$\frac{(9)}{V_T} \leq \Delta t \leq \frac{(500)}{V_T}$	$\frac{(9)}{V_T} \leq \Delta t \leq \frac{(200)}{V_T}$
2	$\frac{(3.2)}{V_T} \leq \Delta t \leq \frac{(1600)}{V_T}$	$\frac{(3.2)}{V_T} \leq \Delta t \leq \frac{(645)}{V_T}$

where: V_T ~ ft/sec, true airspeed.

Constant-speed pitch rate responses to step force (F_{ES}) input were computed for all of the configurations with the 25 rad/sec feel system. These are presented at the end of this Appendix. The effective time delay (t_1), including the TIFS pitch model-following delay of .06 seconds, and rise time parameter (Δt) were measured from these responses and are tabulated on Table V-B-1 for the Short Aft Tail configurations. Transient peak ratio is not presented, as the values for this parameter were Level 1 for all configurations. The results from this analysis are also presented in Figure V-B-2 where the configurations with pilot ratings are spotted on the effective time delay and rise time plane. Flying qualities levels are indicated on this figure. For the rise time parameter, V_T = 253.2 ft/sec and the terminal flight phase limits were used.

TABLE V-B-1. TIME HISTORY CRITERIA

Pitch rate response to step force input.

t_1 ~ Effective time delay, sec — maximum slope intercept

Δt ~ Effective rise time, sec — time between maximum slope intercept of time axis and steady state value

CONFIGURATION		LEVEL OF DELAY (T_1)					
		A		B		C	
		t_1**	Δt	t_1**	Δt	t_1**	Δt
Short Aft Tail	Med α	.14	1.59	.23	1.74		
	High α	.14	1.03	.22	1.16		
	Med q	.14	2.06				
	High q	.13	.94			(.39	1.06)*
	Ex-High q	.14	.44				

*T_1 = .35 (shuttle lag/delay)

**t_1 evaluated with 25 rad/sec feel system. t_1 values for the 15 rad/sec feel system are 0.04 sec larger.

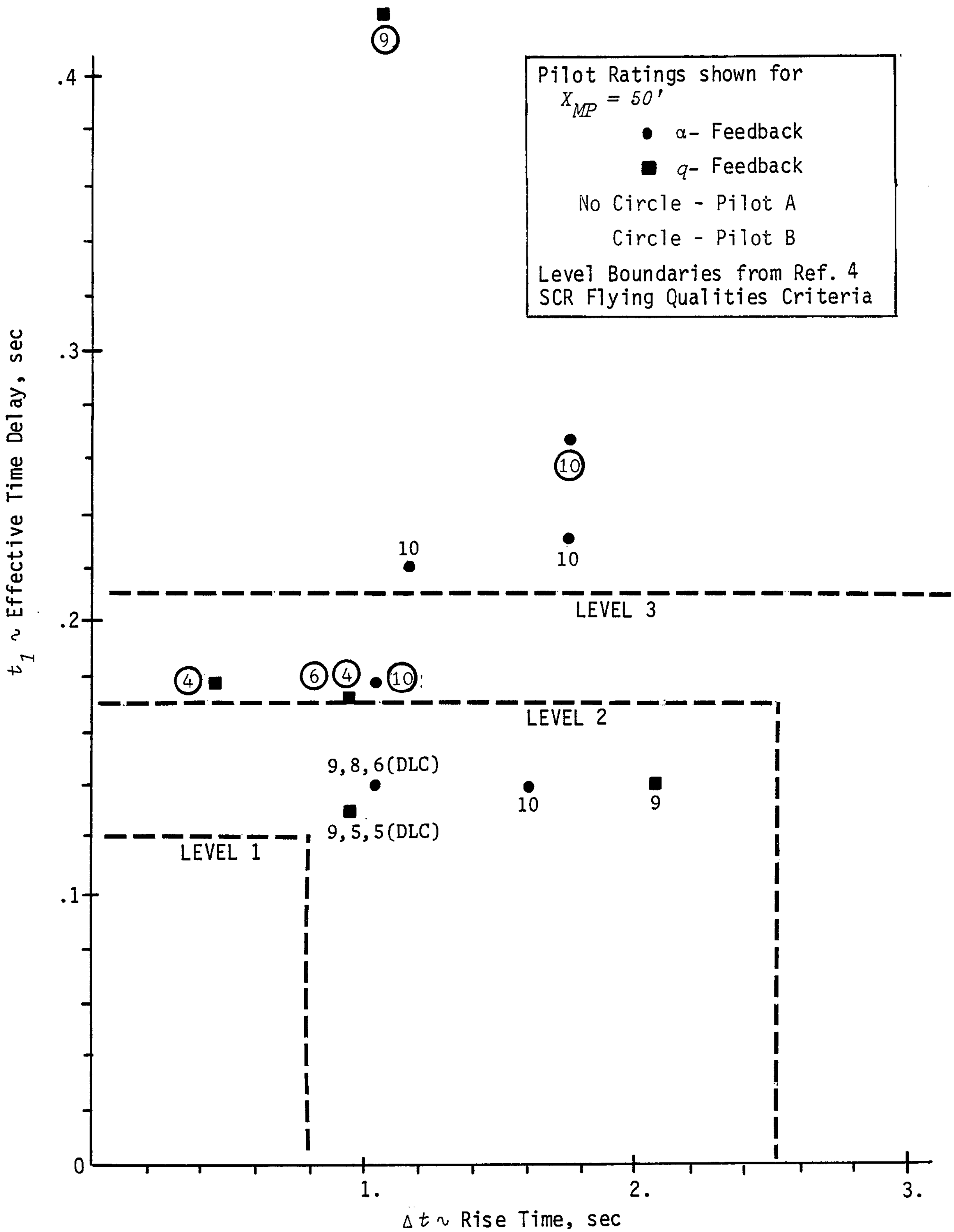
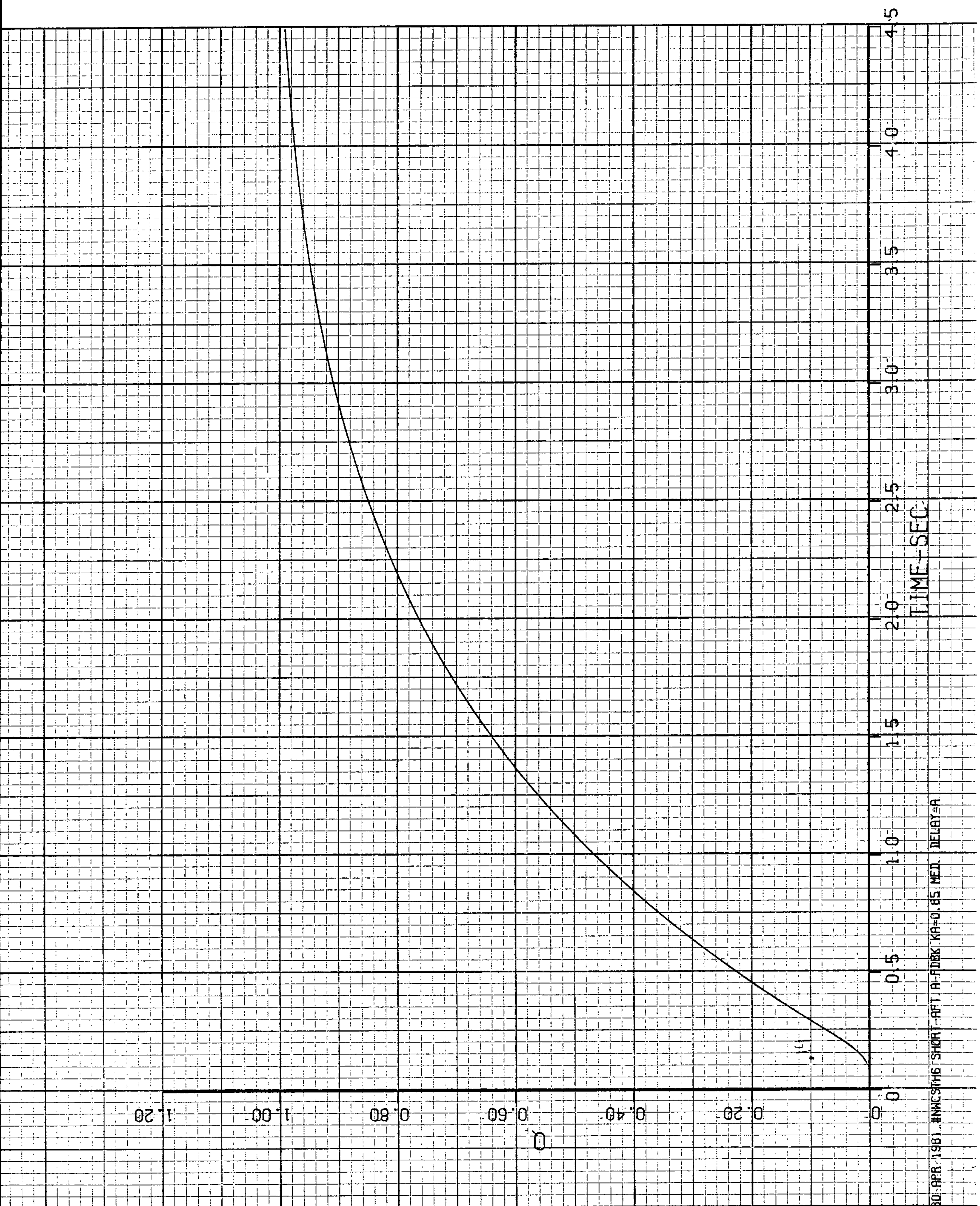


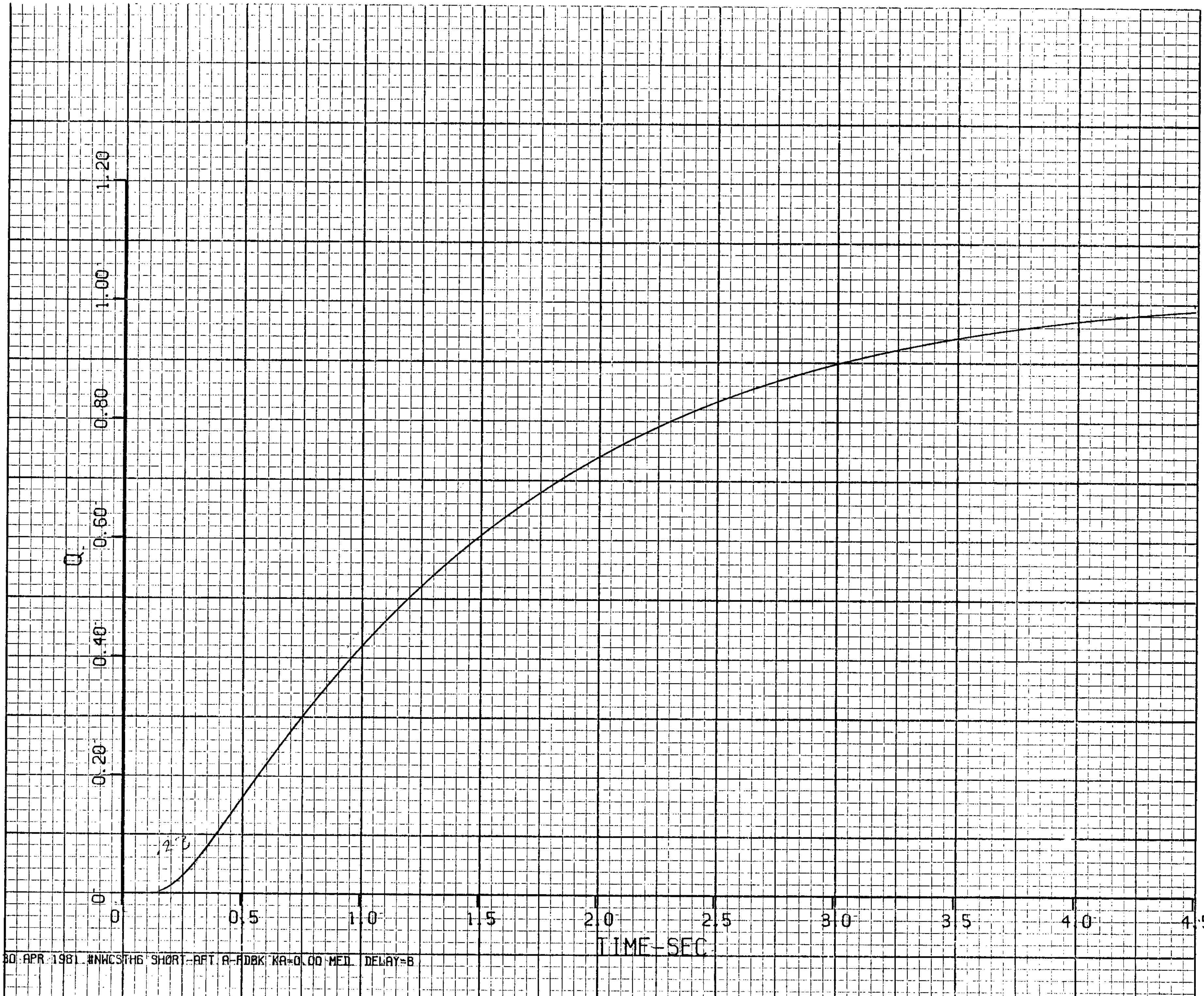
Figure V-B-2. SHORT AFT TAIL CONFIGURATIONS VS TIME HISTORY CRITERIA

PITCH RATE RESPONSE — TIME HISTORY CRITERIA PLOTS

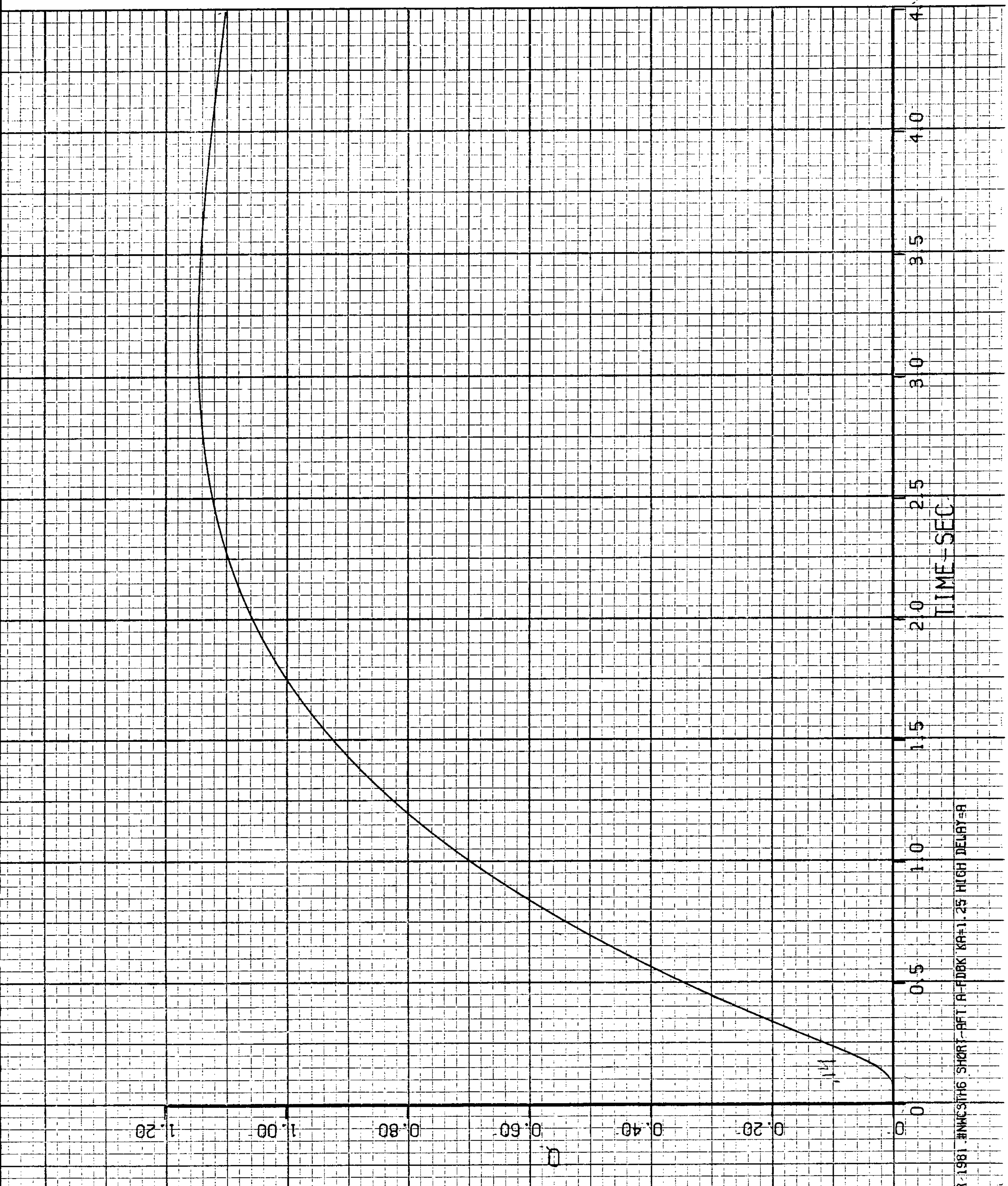
The following figures present the constant speed time histories of pitch rate response to a step force input for each Short Aft Tail configuration evaluated. The captions beneath each time history define the configuration. The time histories were normalized so that the steady state for each configuration (except the unaugmented ones) was 1. The 25 rad/sec feel system was used to calculate the time histories. The 15 rad/sec feel system would increase the t_1 value by 0.04 sec. The TIFS pitch model-following delay of .06 seconds is included. From these time histories effective time delay (t_1) and rise time (Δt) parameters were measured.



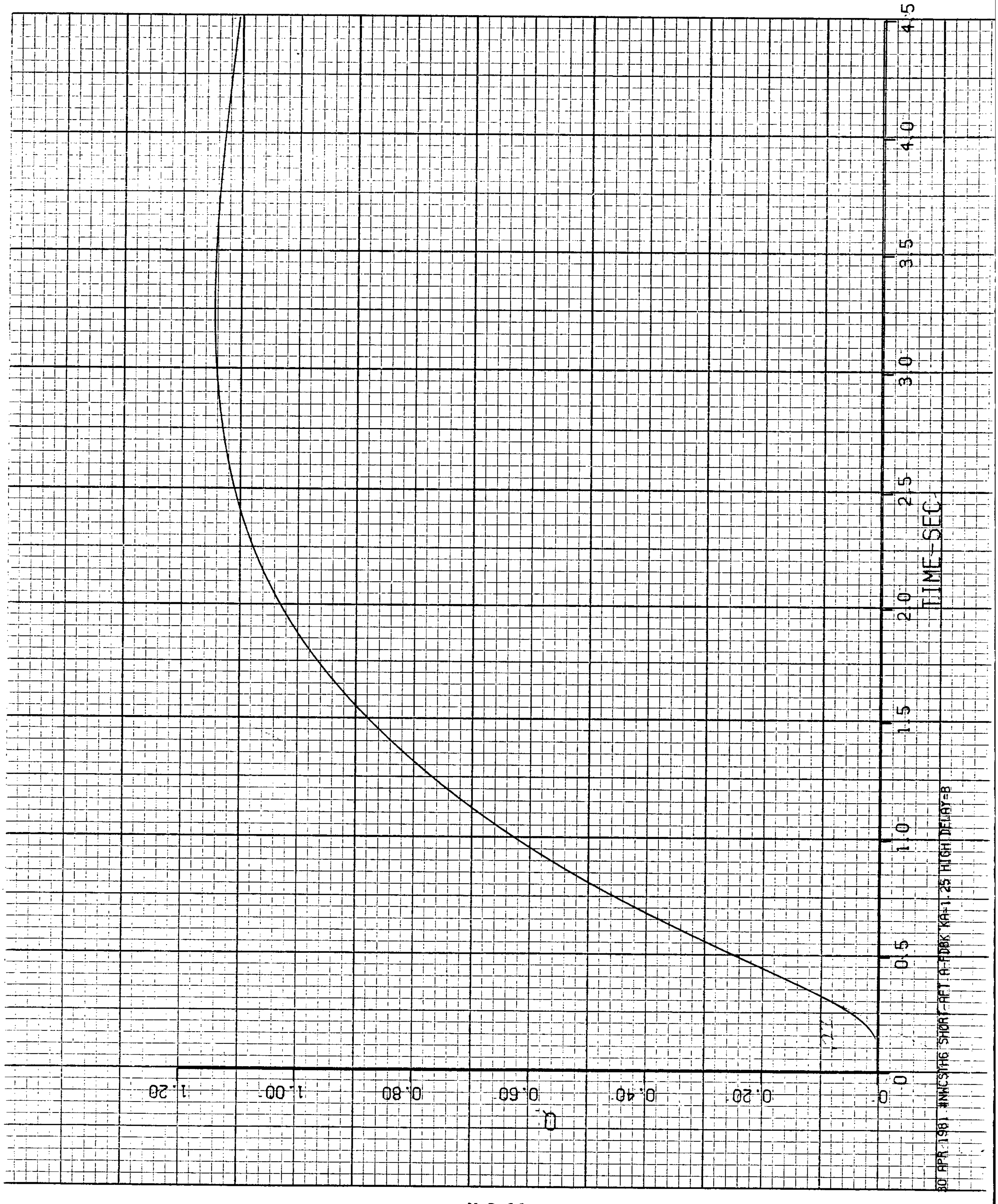
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
0
0.20
0.40
0.60
0.80
1.00
1.20
30 APR 1981 #NWCS7H6 SHORT-AFT A-ADBK KA=0.85 MED. DELAY=A

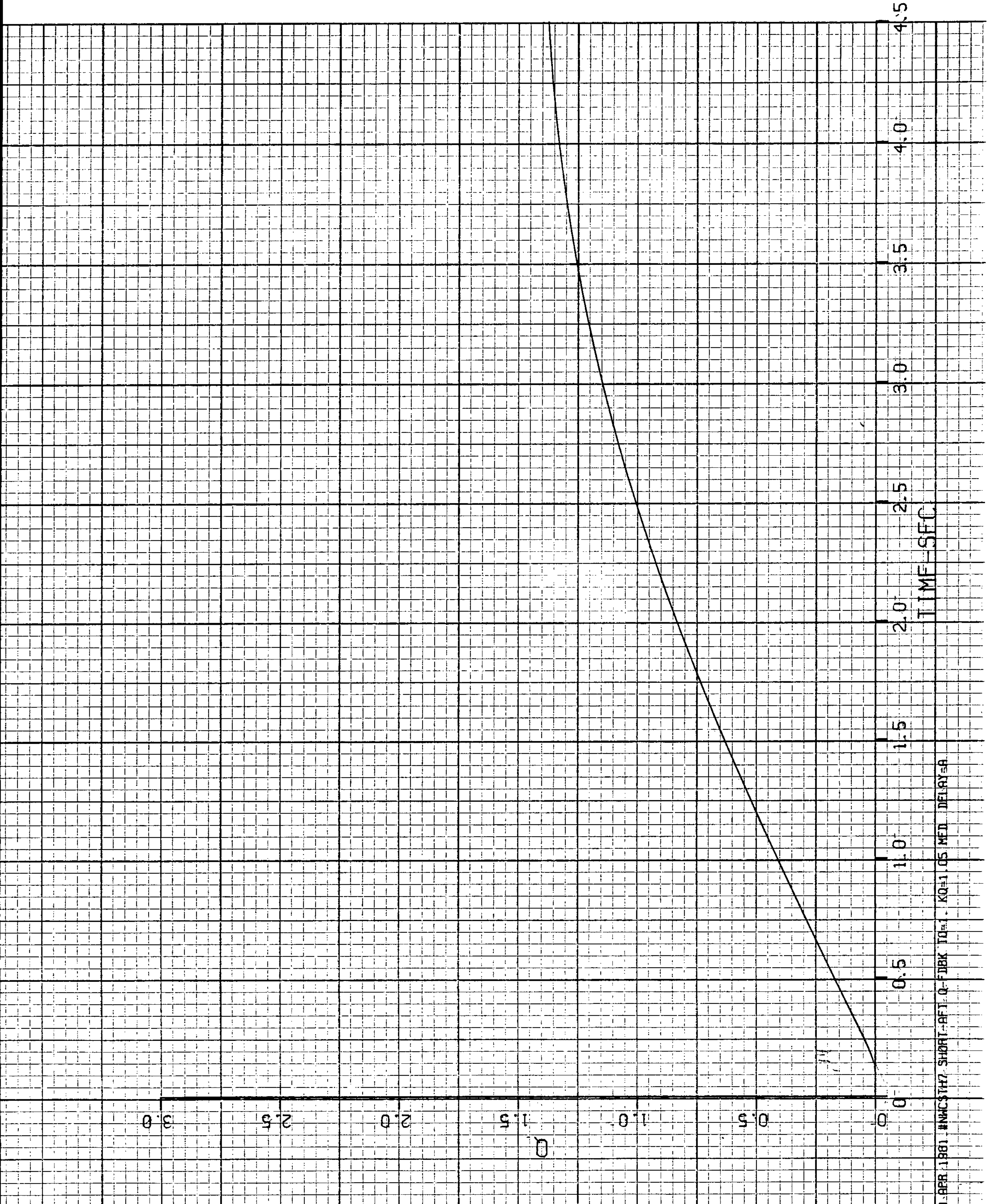


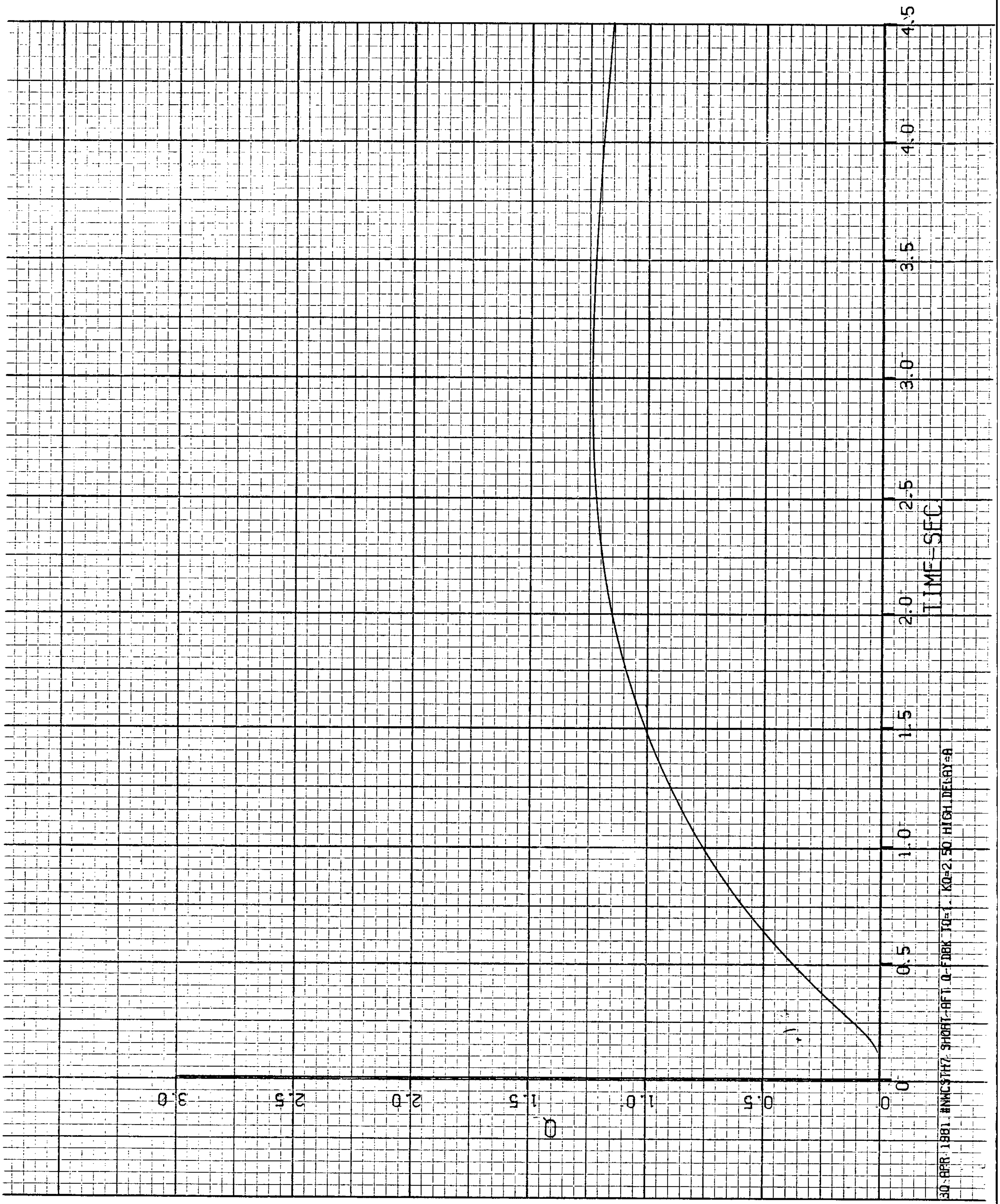
1.20
1.00
0.80
0.60
0.40
0.20
0
Q
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
TIME-SEC
30 APR 1981 #NWCSTHG SHORT-AFT A-ADBK KA=0.00 MED DELAY=B



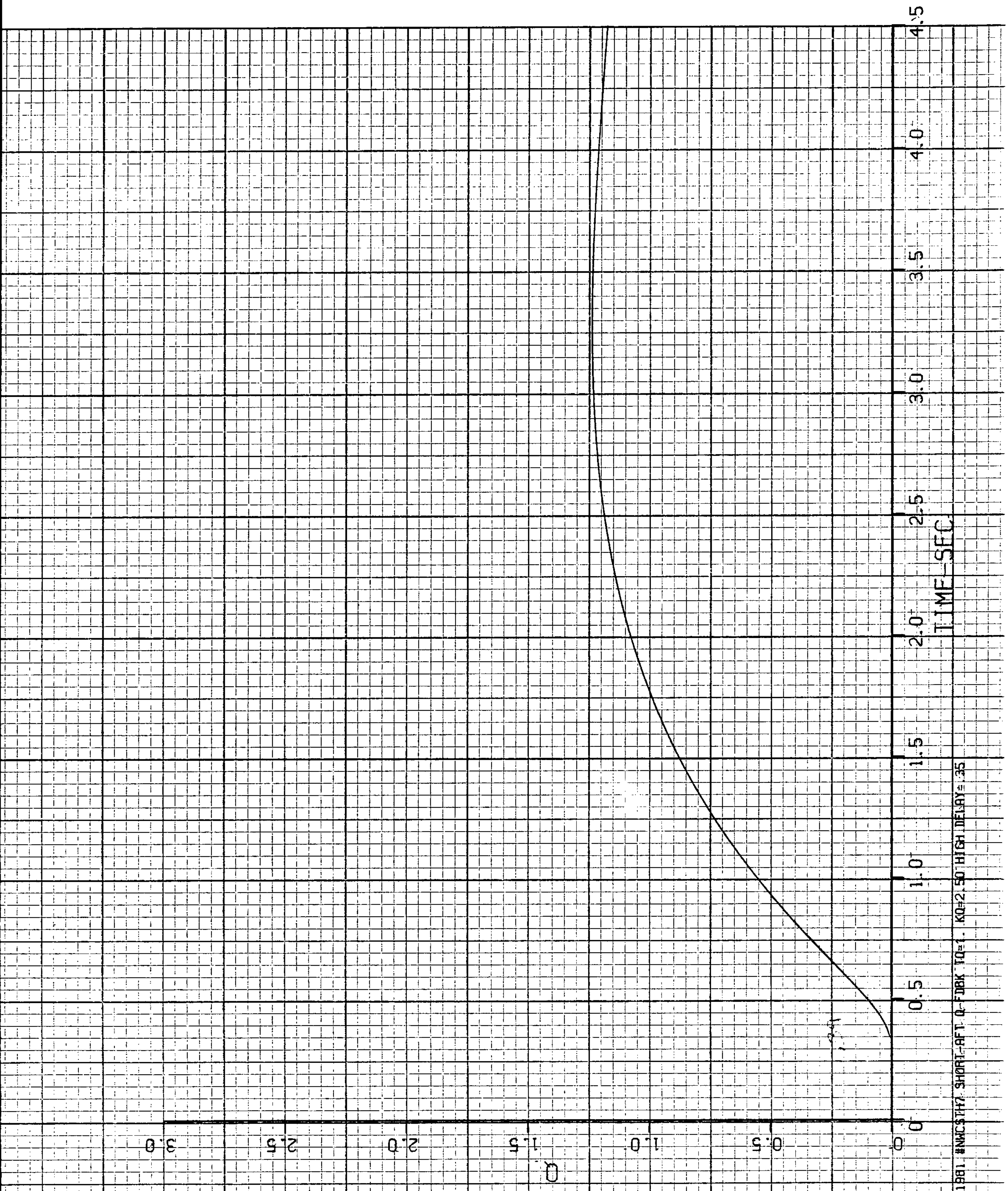
30 APR 1981 #NWCSTH6 SHORT-AFT A-FDBK KA=1.25 HIGH DELAY=A
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Q
0
0.20
0.40
0.60
0.80
1.00
1.20
.14


30 APR 1981 #NWCSTH6 SHORT-AFT A-FDBK KA=1.25 HIGH DELAY=B
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Q
0
0.20
0.40
0.60
0.80
1.00
1.20

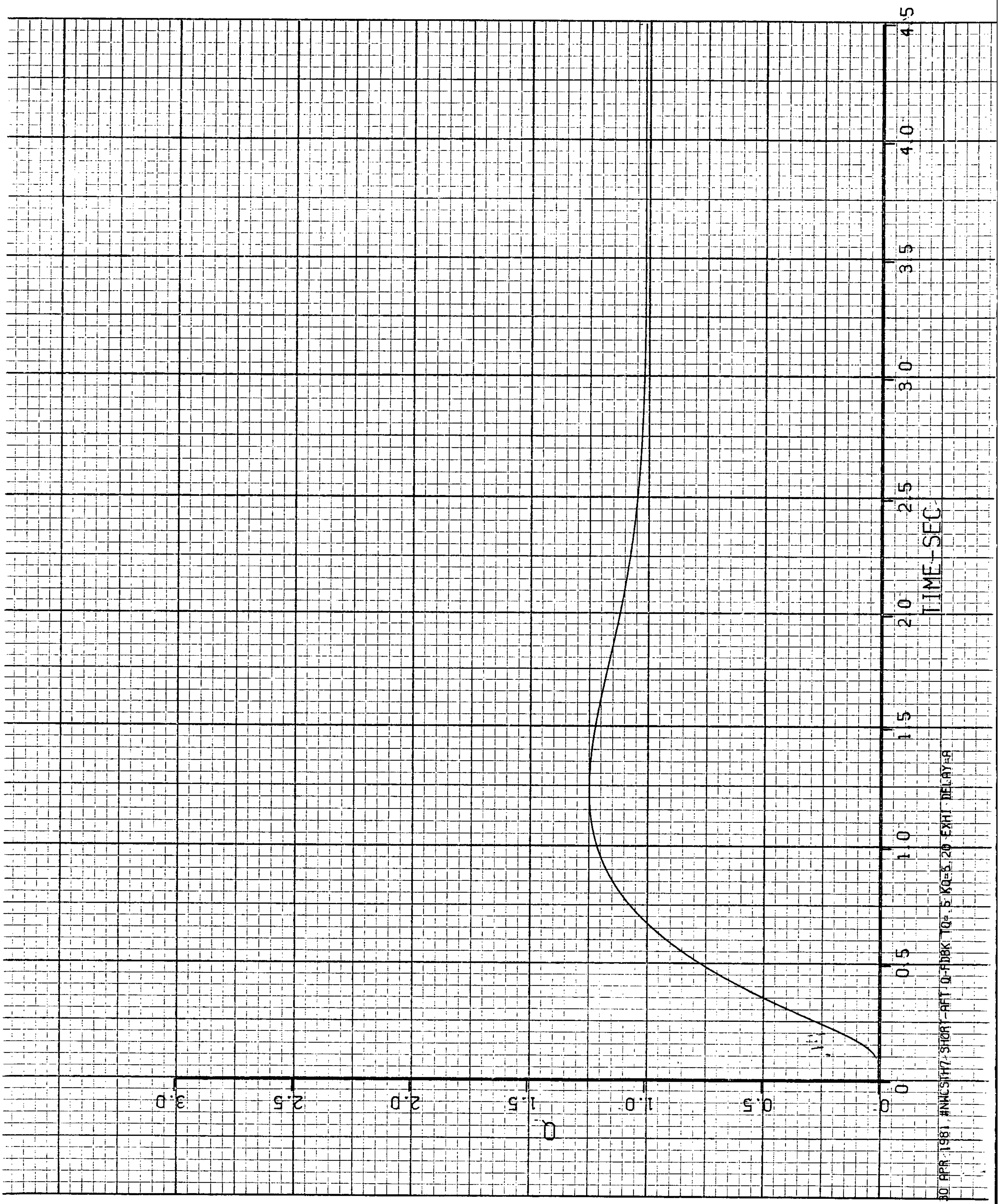

30 APR 1981 #NWCSTH7 SHØRT-AFT Q-FDBK TD=1. KQ=1.05 MED DELAY=0
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Q
0
0.5
1.0
1.5
2.0
2.5
3.0



Q
0
0.5
1.0
1.5
2.0
2.5
3.0
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
30 APR 1981 #NWCSTH7 SHORT-AFT Q-FDBK TQ=1. KQ=2.50 HIGH DELAY=A



0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
Q
30 APR 1981 #NWCSTH7 SHORT-AFT Q-FDBK TQ=1. KQ=2.50 HIGH DELAY=.35


30 APR 1981 #NWCSTH7 SHORT-AFT Q-FDBK TQ=.5 KQ=5.20 EXH DELAY=A
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Q
0
0.5
1.0
1.5
2.0
2.5
3.0

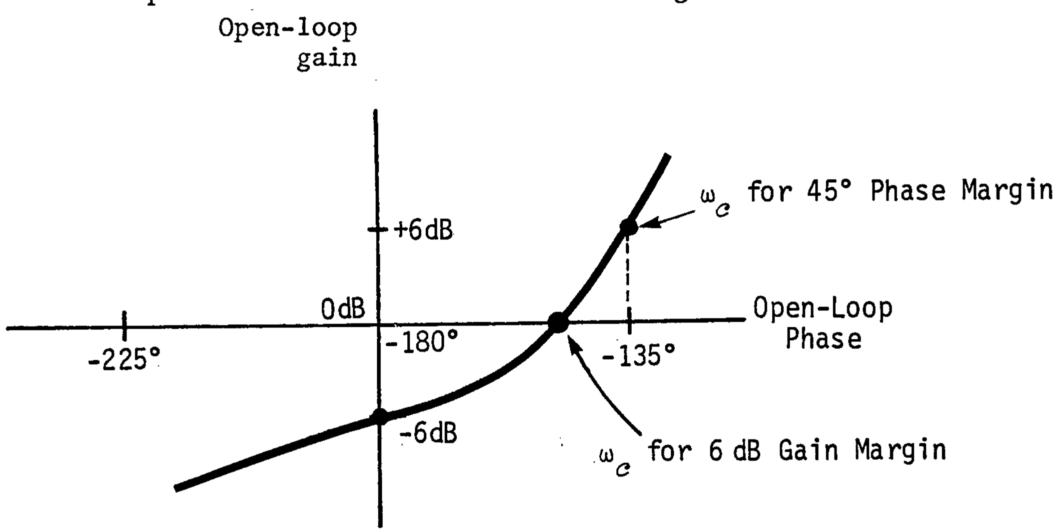
Appendix V-C
OPEN-LOOP (AIRCRAFT ONLY) PITCH ATTITUDE ANALYSIS

In this analysis the open-loop, aircraft-only, pitch attitude bandwidth was obtained and combined with equivalent time delay for correlation with pilot ratings and comments. This is the bandwidth criterion suggested by STI in Reference 7 where the bandwidth is defined as the lower of the frequencies which yields a 6 dB gain margin or 45 deg. phase margin. To easily obtain these values for each configuration, the aircraft's open-loop pitch attitude to stick force transfer function (θ/F_{ES}) was plotted on a Nichols diagram.

The frequency for 6 dB gain margin was obtained by shifting the curve vertically so that it went through -180 deg. phase angle with a magnitude of -6 dB. Then the frequency at which this shifted curve passed through 0 dB was measured. This crossover frequency was the bandwidth based on the gain margin.

The frequency for 45 deg. phase margin was obtained by measuring the frequency at which the curve passed through -135 degrees open-loop phase angle.

This procedure is shown in the following sketch:



A tabluation of the results of these measurements for the Short Aft Tail configurations is presented in Table V-C-1. For all of the configurations, the bandwidth was determined by the frequency at 45 deg phase margin. Plots of equivalent time delay (T_D) from the equivalent system analysis (Appendix V-A) versus these calculated open-loop bandwidths are presented in Figure V-C-1. Pilot ratings for the individual configurations evaluated are pointed out on these plots. Also plotted are the Level 2 and 3 boundaries from Reference 7 for fighter landing approach data.

TABLE V-C-1

OPEN LOOP BANDWIDTH (RAD/SEC) FOR θ/F_{ES}

FREQUENCIES FOR 6 dB GAIN MARGIN AND 45^{o} PHASE MARGIN

Open Loop Bandwidth Defined as Lower of the Two Values

CONFIGURATION	LEVEL OF DELAY (T_1)					
	A		B		C	
	6 dB GM	45^{o} PM	6 dB GM	45^{o} PM	6 dB GM	45^{o} PM
Short Aft Tail Med α	1.35	.57	1.0	.52		
High α	1.42	.80	1.1	.73		
Med q	.61	.47				
High q	1.43	.82			(.85	.68)*
Ex-High q	1.84	1.68				

*T_1 = .35 (shuttle lags/delay)

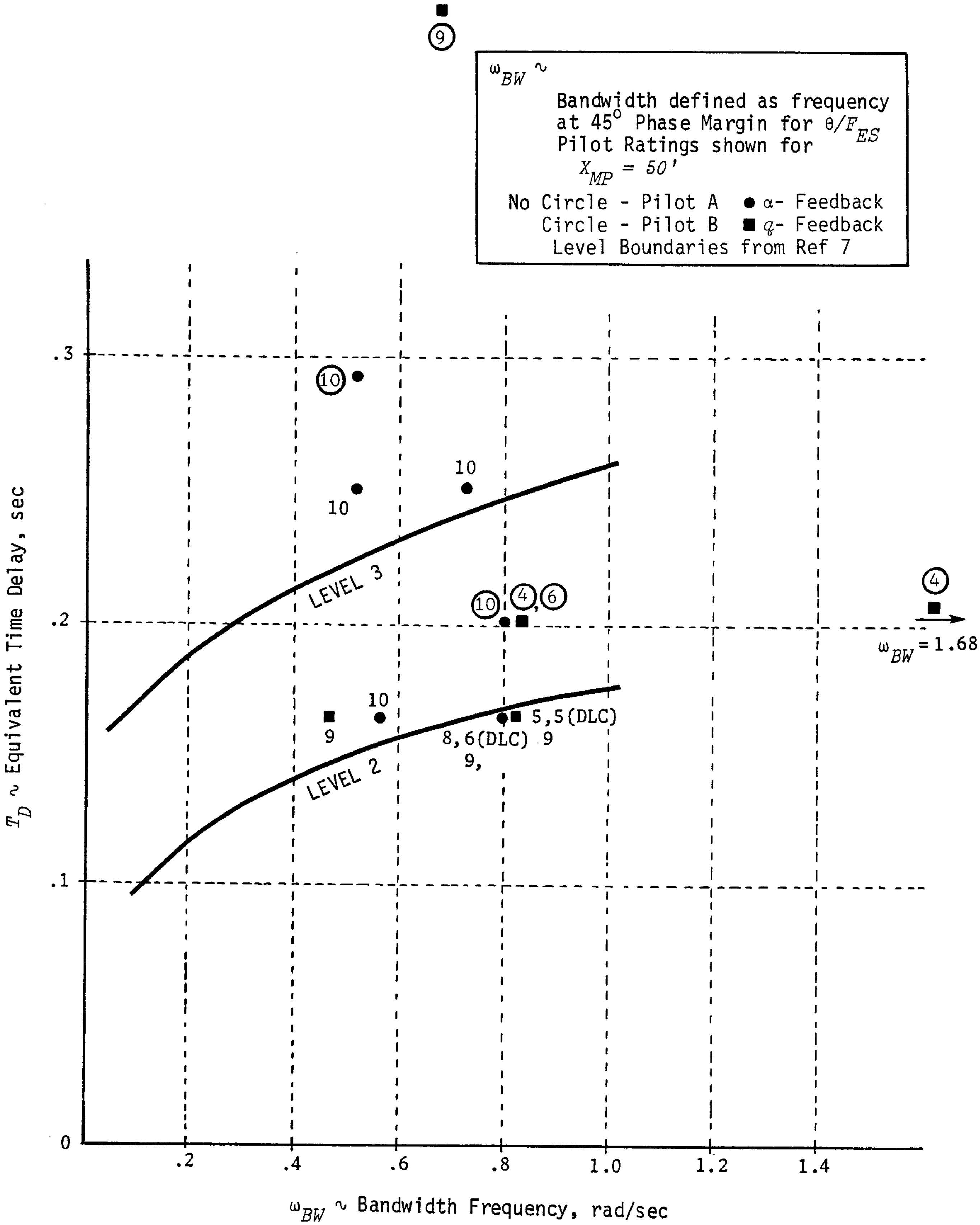


Figure V-C-1. SHORT AFT OPEN LOOP θ/F_{ES} BANDWIDTH VS TIME DELAY

Appendix V-D

OPEN-LOOP (AIRCRAFT PLUS UNCOMPENSATED PILOT) PITCH ATTITUDE ANALYSIS

A simplified method of analyzing the closed-loop, pilot-aircraft behavior that has been used to correlate pilot ratings was developed in Reference 5. In this method, only the airplane pitch attitude and uncompensated pilot model transfer functions are necessary. The open-loop, uncompensated pilot-aircraft transfer function ($\theta/\theta_\varepsilon$) is plotted on a Nichols diagram. The slope of this line, $\left(\frac{\Delta A}{\Delta \phi}\right)_\theta$, at some reference frequency is a measure of the closed-loop resonance. The more positive the slope becomes, the lower the closed-loop resonance will be. The differential phase angle $\Delta\phi_\theta$ between -90 deg and the phase angle at the reference frequency is a measure of the amount of lead compensation that the pilot must apply: the larger the differential phase angle, the larger the lead must be.

Nichols diagrams were obtained for each evaluated configuration with the uncompensated pilot model: (The 25 rad/sec feel system was used in this analysis).

$$\theta/\theta_\varepsilon = Y_{P_\theta} \quad \theta/F_{ES}$$

$$Y_{P_\theta} = K_{P_\theta} \; e^{-.25s} \left(\frac{5s+1}{s}\right)$$

The transfer function was normalized by adjusting the gain K_{p_θ} such that the curves would pass through 0 dB at ω = 1 rad/sec. The measurements taken do not depend upon K_{p_θ}. A reference frequency was chosen as 1.2 rad/sec. These Nichols diagrams are presented at the end of this Appendix. A tabulation of the slope and phase measurements taken off of these plots for the Short Aft Tail configurations is shown in Table V-D-1. These measurements are also plotted on Figure V-D-1. The pilot ratings for each configuration are also indicated on this figure along with flying qualities level boundaries from Reference 8.

The open-loop slope $\left(\frac{\Delta A}{\Delta \phi}\right)_\theta$ is high enough for all of the configurations that it is not a factor. The differential phase $\Delta\phi_\theta$ is, however, an important variable in this analysis. As the phase grows more negative, the

pilot ratings become worse. The large negative phase angles correspond to the configurations with extra lags and delays inserted (T_1 = B and C). They also correspond to the configurations with lower levels of augmentation. This indicated that these configurations will require large amounts of pilot lead in the closed loop to achieve desired performance.

TABLE V-D-1

OPEN LOOP θ/F_{ES} PLUS UNCOMPENSATED PILOT

SLOPE $\left(\frac{\Delta A}{\Delta \measuredangle}\right)_\theta$ VS. DIFFERENTIAL PHASE ($\Delta\measuredangle\theta$)

AT REFERENCE FREQUENCY, ω_θ = 1.2 RAD/SEC

$$\frac{\theta}{\theta_\varepsilon}(s) = K_{P_\theta} \frac{5s+1}{s} e^{-.25s} \frac{\theta}{F_{ES}}(s)$$

25 rad/sec Feel System

CONFIGURATION	LEVEL OF DELAY (T_1)					
	A		B		C	
	$\frac{\Delta A}{\Delta \measuredangle}$, dB/deg	$\Delta\measuredangle\theta$, deg	$\frac{\Delta A}{\Delta \measuredangle}$, dB/deg	$\Delta\measuredangle\theta$, deg	$\frac{\Delta A}{\Delta \measuredangle}$, dB/deg	$\Delta\measuredangle\theta$, deg
Short Aft Tail Med α	.38	-100	.33	-107		
High α	.28	-93	.25	-101		
Med q	.31	-127				
High q	.24	-93			(.19	-113)*
Ex-High q	.15	-51				

*T_1 = .35 (shuttle lag/delay)

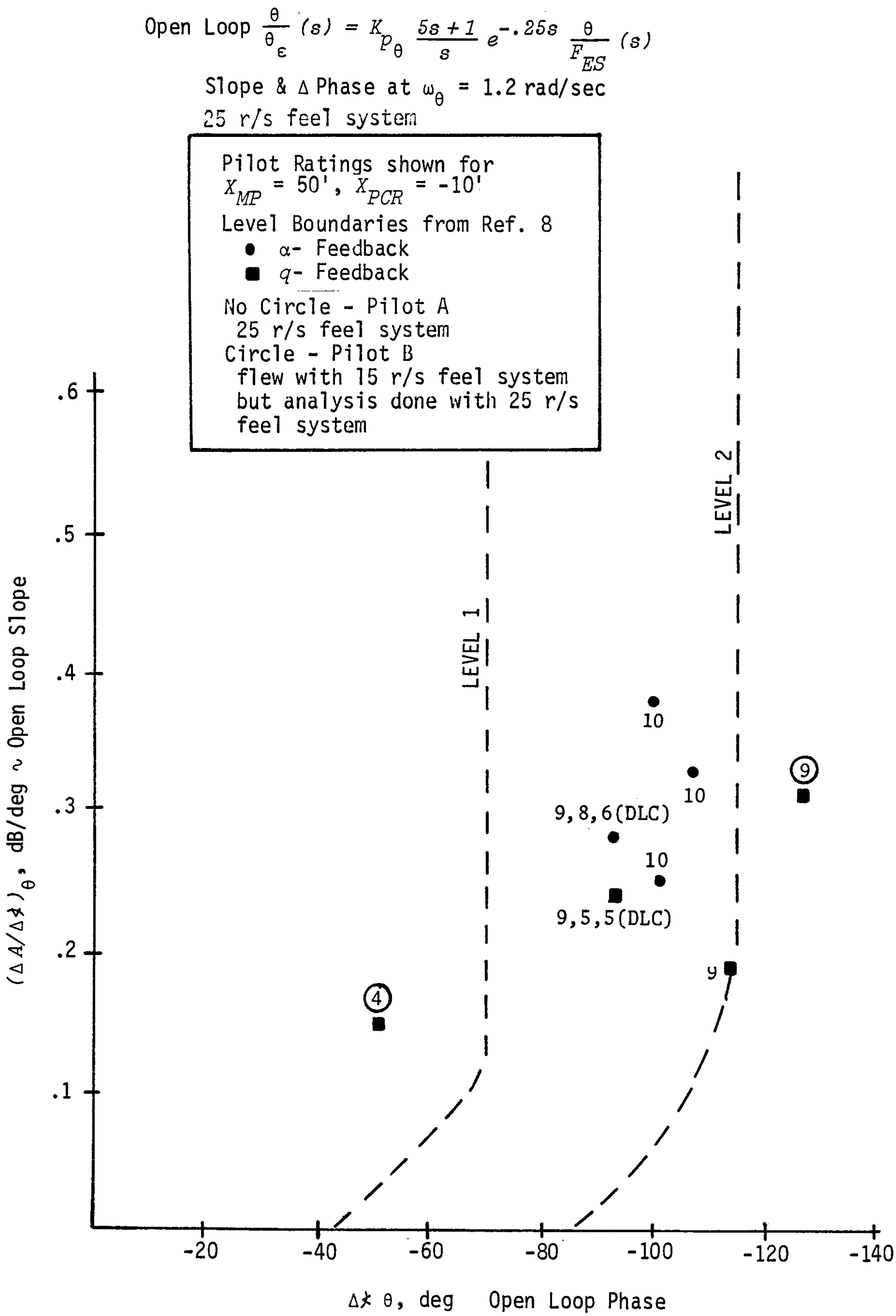


Figure V-D-1. SHORT AFT TAIL OPEN LOOP θ/F_{ES} PLUS UNCOMPENSATED PILOT, SLOPE VS PHASE

OPEN-LOOP AIRCRAFT PLUS UNCOMPENSATED PILOT NICHOLS DIAGRAMS, $\theta/\theta_\varepsilon$

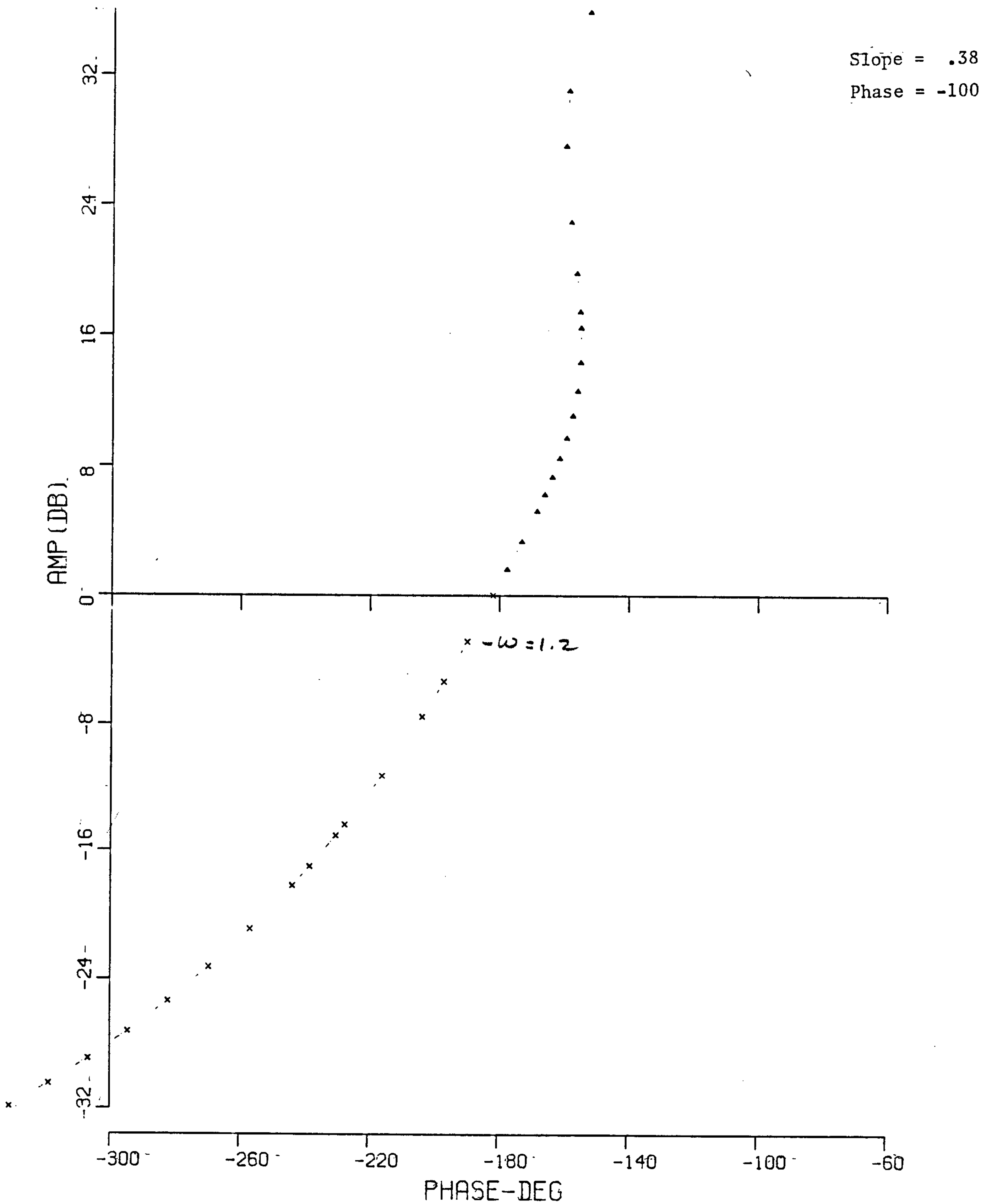
The following figures present the open-loop aircraft plus uncompensated pilot Nichols diagrams for each Short Aft Tail configuration evaluated. The pilot model contains a .25 second delay and low frequency integration capability $\left(\frac{5s+1}{s}\right)$. The gain ($K_{p_\theta}$) was adjusted to normalize the curves to force them through 0 dB at ω = 1. rad/sec. (The 25 rad/sec feel system was used).

$$\theta/\theta_\varepsilon = K_{p_\theta} e^{-.25s} \left(\frac{5s+1}{s}\right) \theta/F_{ES}$$

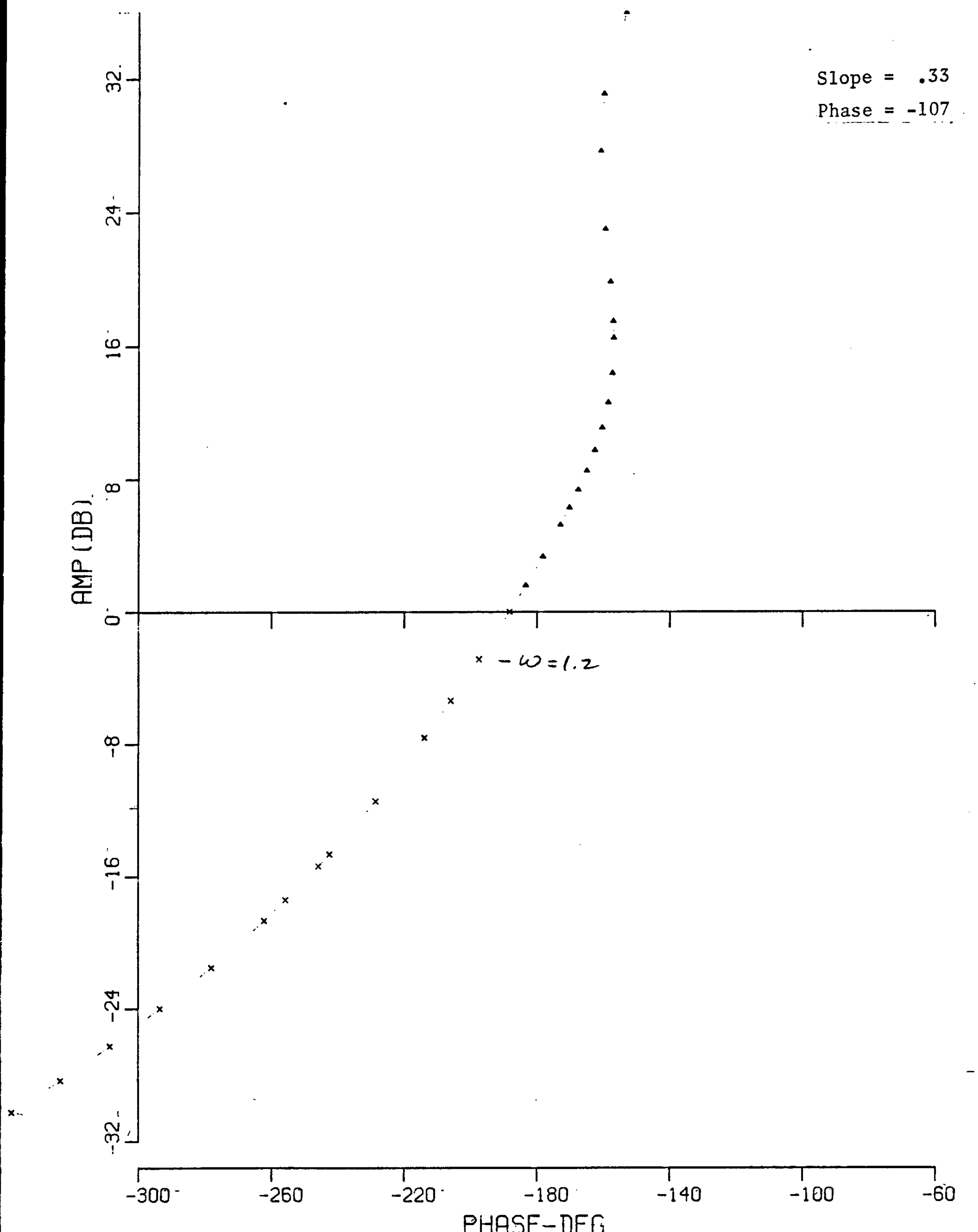
The measurements taken from these plots were the slope $\left(\frac{\Delta A}{\Delta \measuredangle}\right)_\theta$, dB/deg and the differential phase at 1.2 rad/sec ($\Delta\measuredangle_\theta$ = [phase @ ω = 1.2 rad] + 90 deg). The captions on each plot define the configuration. The order of the frequency points are:

ω *(rad/sec)* $\blacktriangle$ = .1, .12, .14, .16, .2, .24, .28, .3, .35, .4, .45, .6, .65, .7, .8, .9

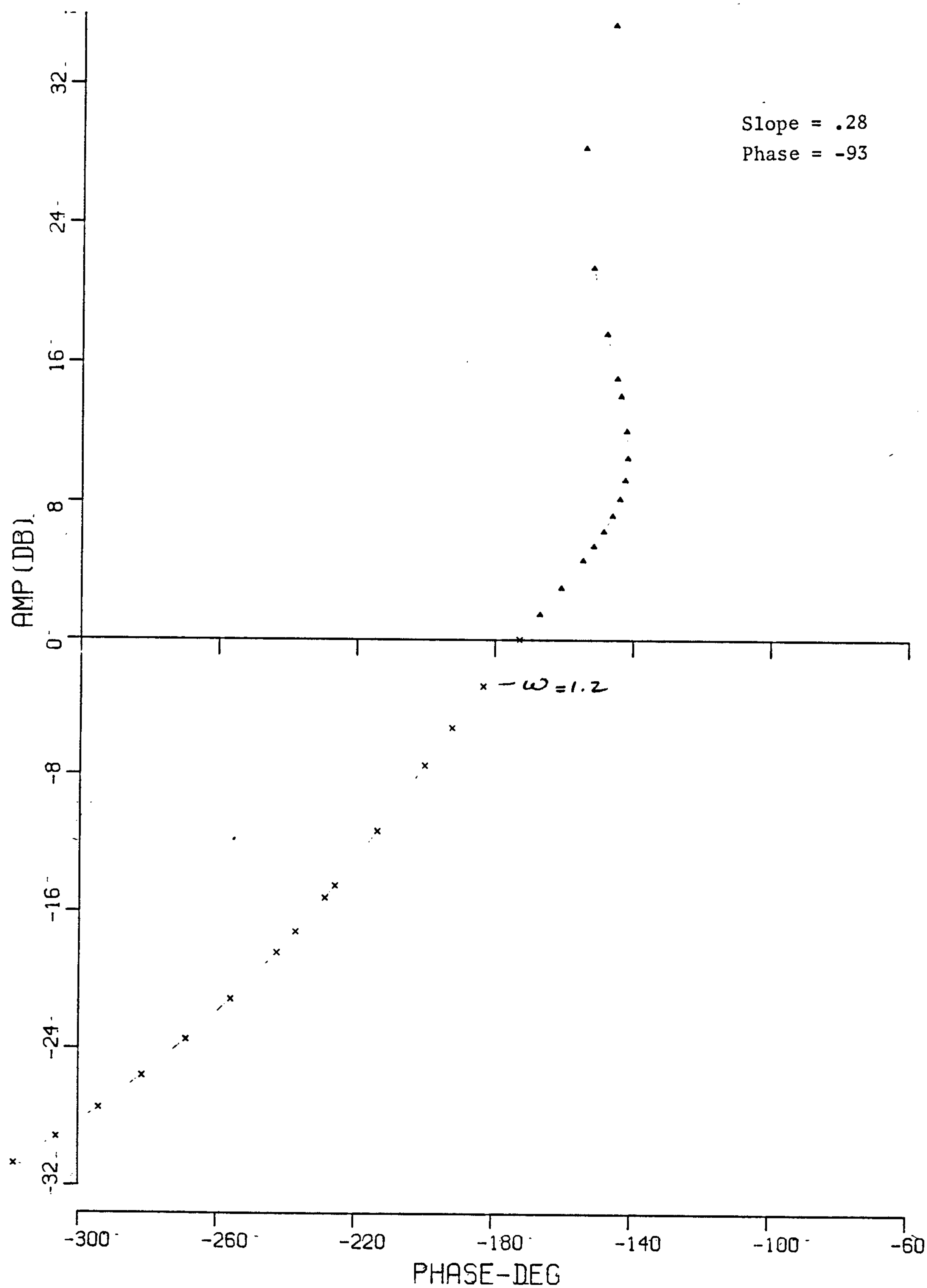
X = above frequencies x 10.



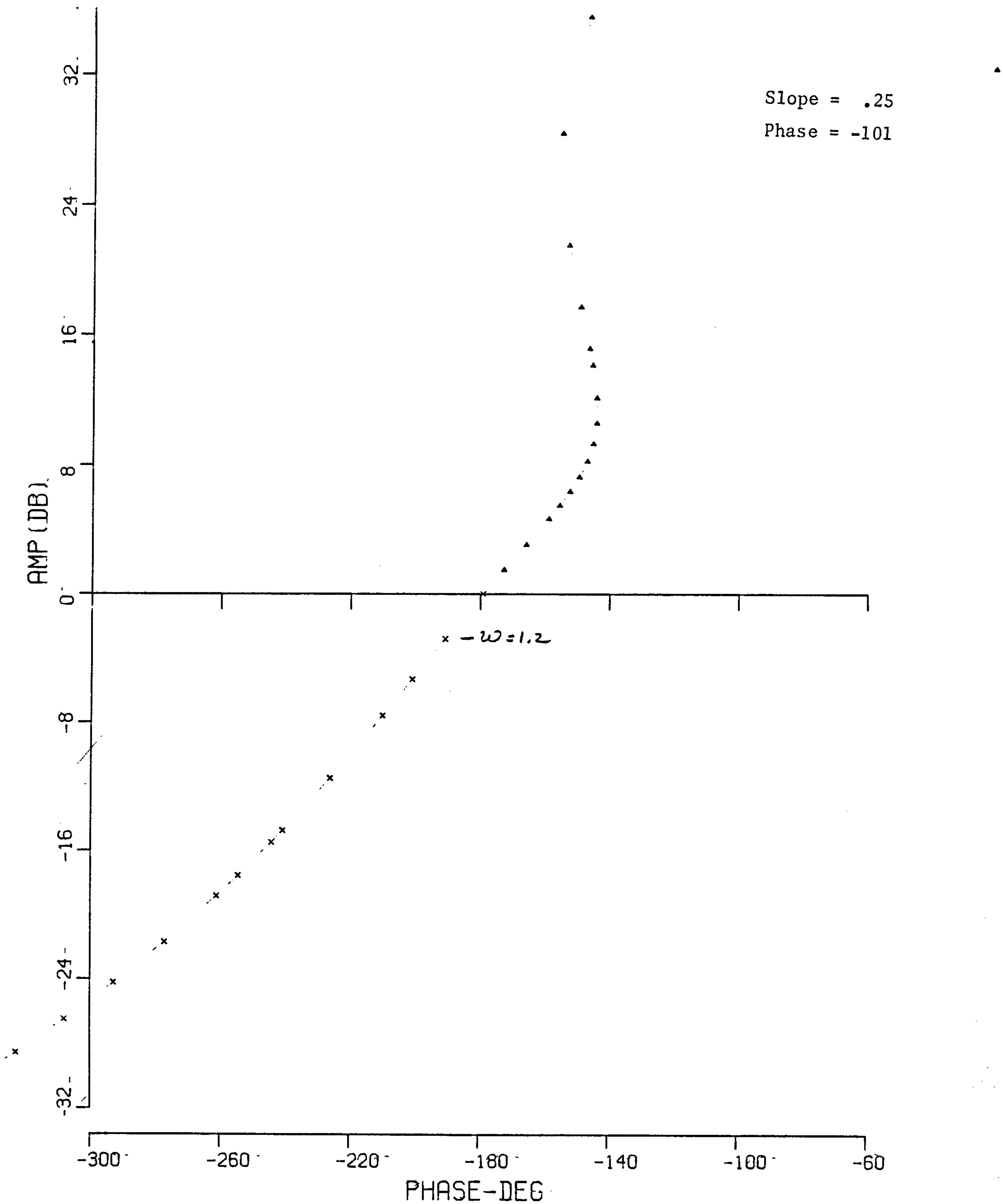
22 APR 1981 L.F. INT - SHORT AFT - ALPHA FDBK - KA=0.85 - MED - DELAY=A



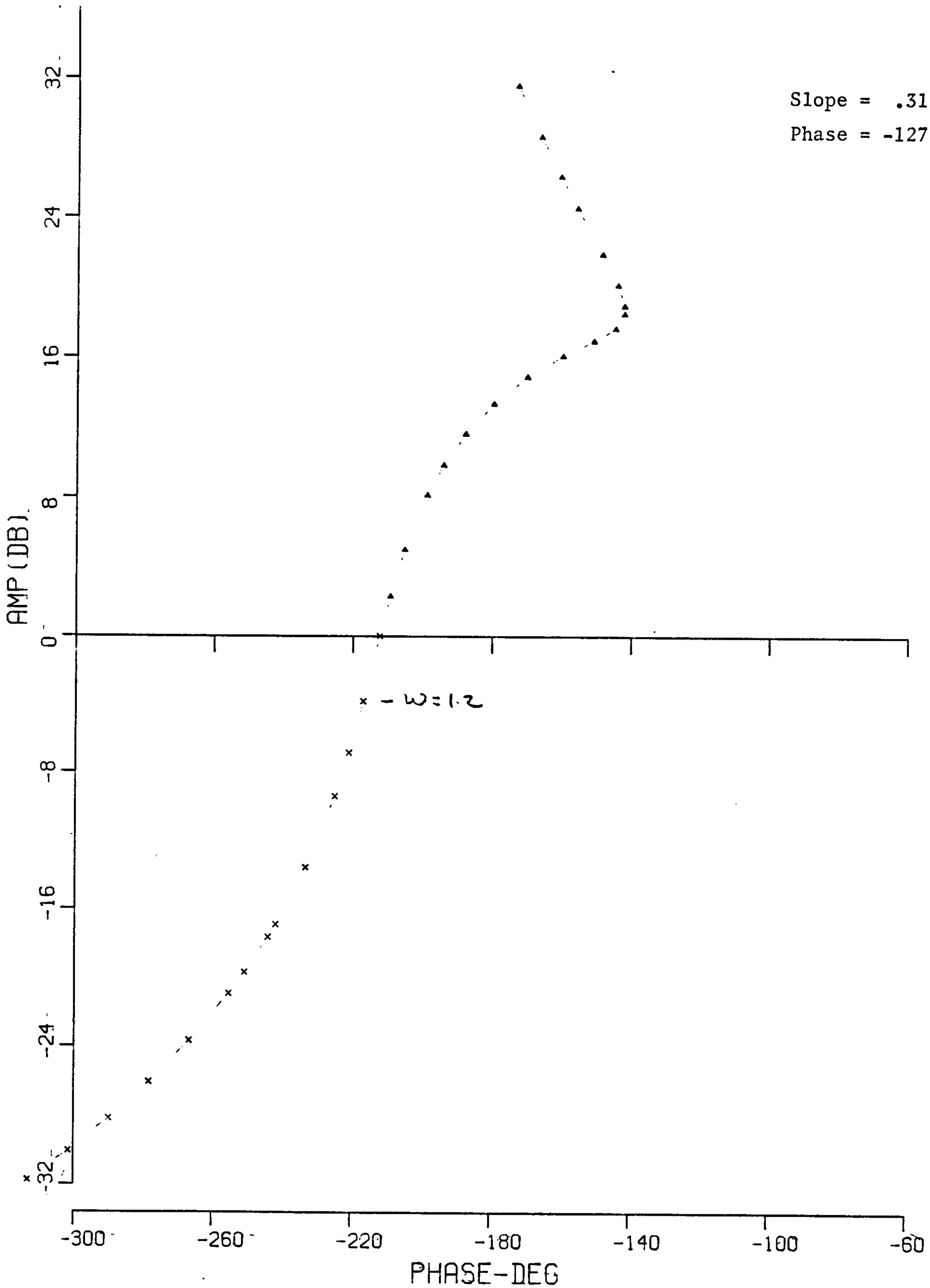
22 APR 1981 L.F. INT - SHORT AFT - ALPHA FDBK - KA=0.85 - MED - DELAY=B



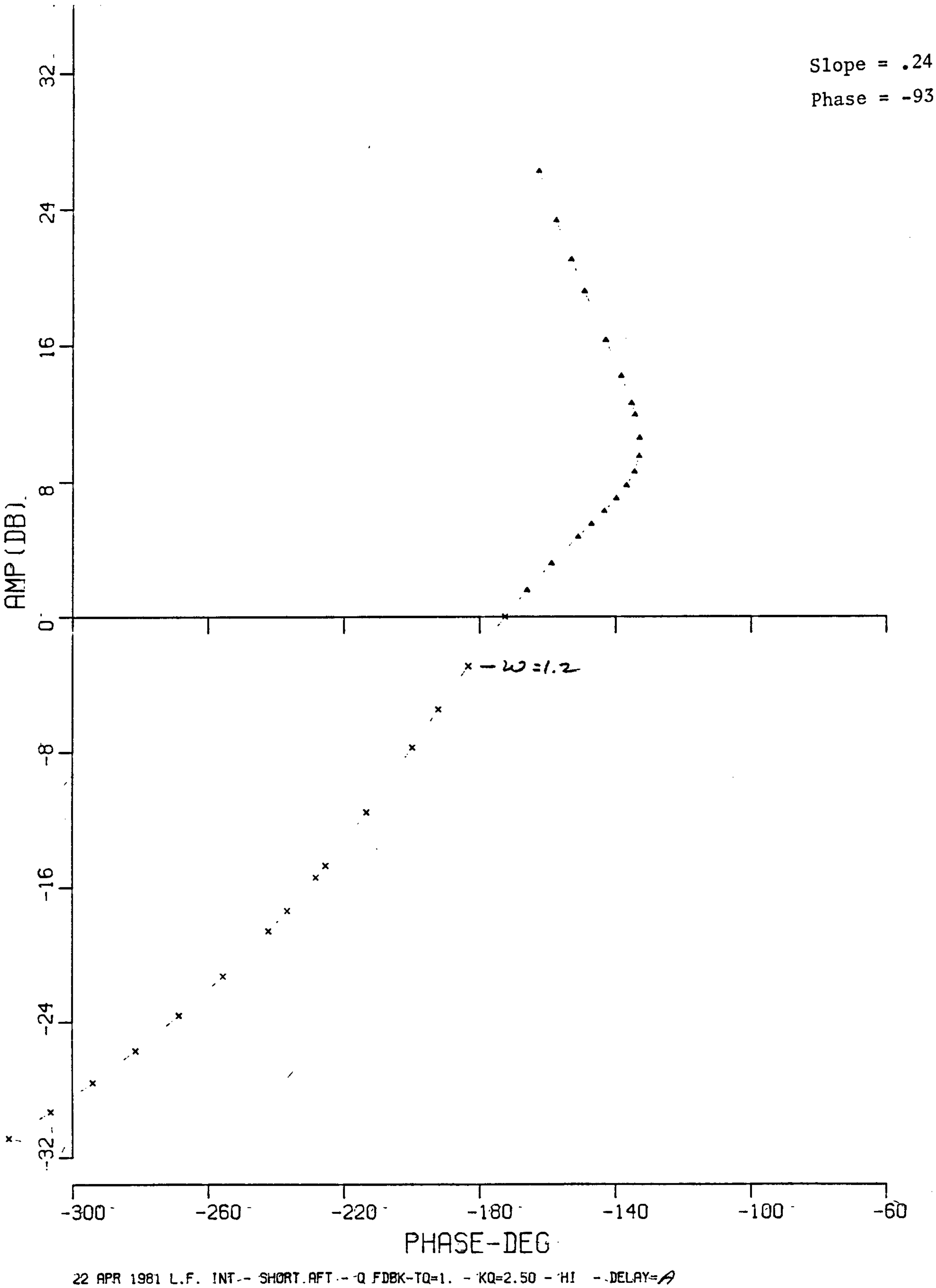
22 APR 1981 L.F. INT - SHORT AFT - ALPHA FDBK - KA=1.25 - HI - DELAY=A

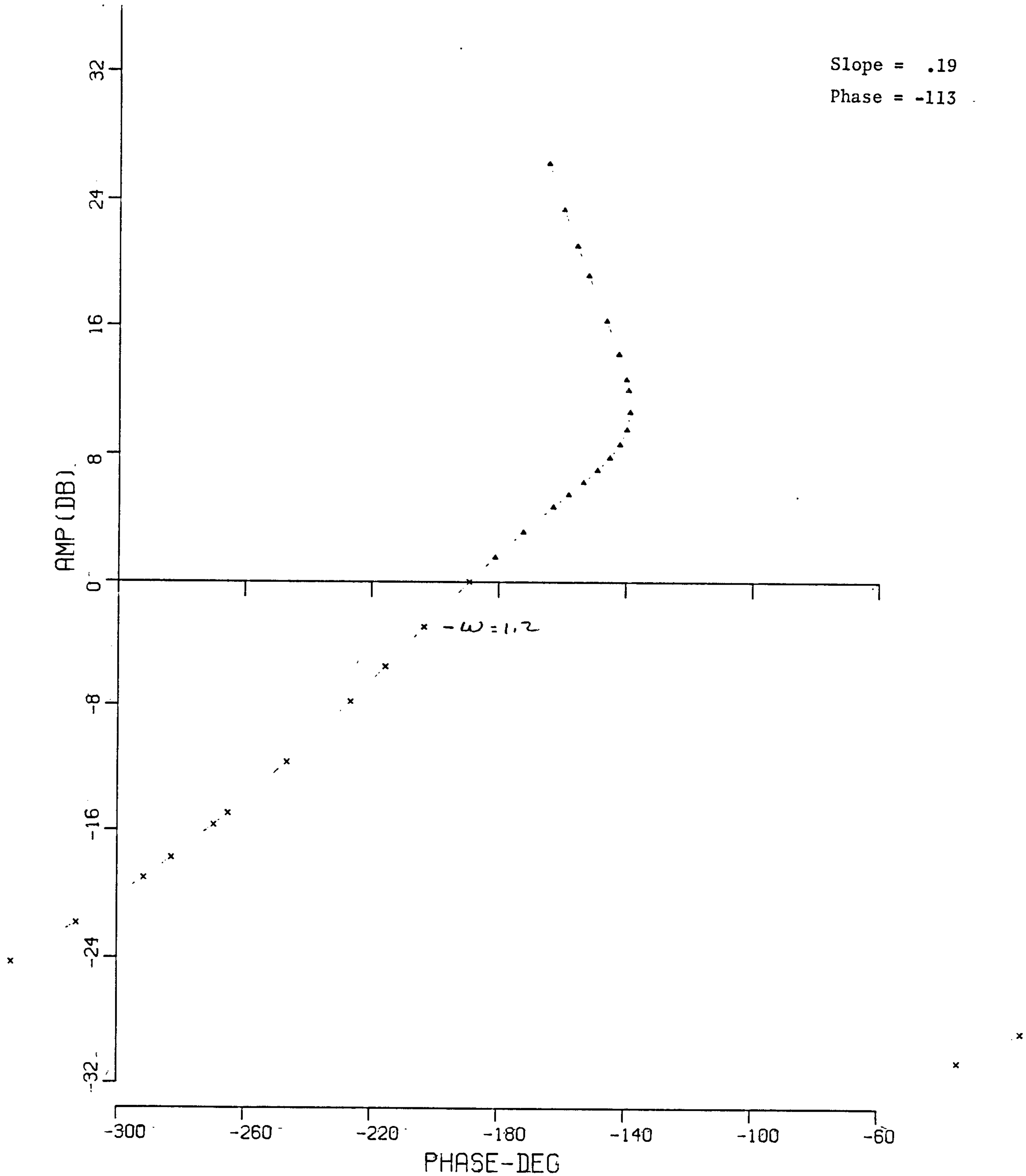


22 APR 1981 L.F. INT - SHORT AFT - ALPHA FDBK - KA=1.25 - HI - DELAY=B

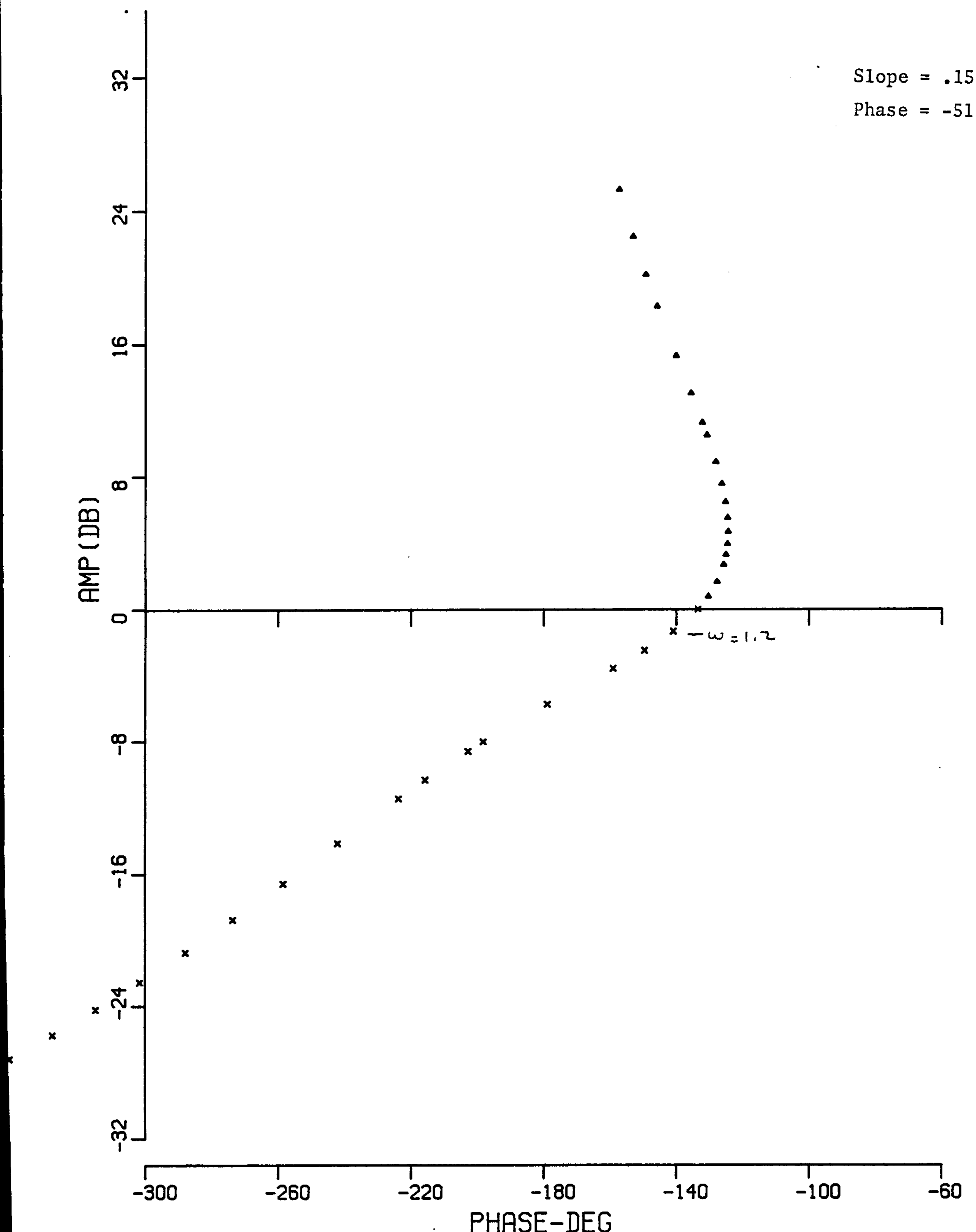


22 APR 1981 L.F. INT - SHORT AFT - Q FDBK-TQ=1. - KQ=1.05 - MED. - DELAY=A


Slope = .24
Phase = -93
x — ω = 1.2
AMP (DB)
32
24
16
8
0
-8
-16
-24
-32
-300
-260
-220
-180
-140
-100
-60
PHASE-DEG
22 APR 1981 L.F. INT-- SHORT AFT -- Q FDBK-TQ=1. - KQ=2.50 - HI - DELAY=A



22 APR 1981 L.F. INT - SHORT AFT - Q FDBK-TQ=1. - KQ=2.50 - HI - DELAY= .35



27 APR 1981 L.F. INT - SHORT AFT - Q FDBK-TQ=.5 - KQ=5.2 - EX-HI - DELAY = A

Appendix VI

RECORDING LIST

Digital Channel No.	Variable (all incremental values referenced to engage value)		Recording Scale Factor, units/volt
1	$\Delta\theta_m$	- incremental pitch attitude, model	2.5 deg
2	$\Delta\theta$	- incremental pitch attitude, TIFS	2.5 deg
3	q_m	- pitch rate, model	2. deg/sec
4	q	- pitch rate, TIFS	2. deg/sec
5	$\Delta\alpha_{IMTCG}$	- incremental angle of attack, inertial, model transformed to TIFS c.g.	2. deg
6	$\Delta\alpha_I$	- incremental angle of attack, inertial, TIFS	2. deg
7	ΔV_m	- incremental velocity, model	33.3 ft/sec
8	ΔV	- incremental velocity, TIFS	33.3 ft/sec
9	$\dot{V}_{MTCG}$	- longitudinal acceleration, model transformed to TIFS c.g.	2. ft/sec^2
10	$\dot{V}$	- longitudinal acceleration, TIFS	2. ft/sec^2
11	$\Delta N_{z_{PM}}$	- normal acceleration, pilot model	.25 g
12	ΔN_{z_p}	- normal acceleration, pilot TIFS	.25 g
13	$\dot{h}_{MTCG}$	- rate of climb, model transformed to TIFS c.g.	25 ft/sec
14	$\dot{h}$	- rate of climb, TIFS	25 ft/sec
15	F_{ES}	- pitch stick force	10 lb
16	F_{AW}	- roll wheel force	10 lb
17	$\dot{\alpha}_{IMTCG}$	- angle of attack rate, inertial, model transformed to TIFS c.g.	2. deg/sec
18	$\dot{\alpha}_I$	- angle of attack rate, inertial, TIFS	2. deg/sec
19	$\ddot{h}$	- altitude acceleration, TIFS	10 ft/sec^2
20	$\Delta N_{z_{CG}}$	- normal acceleration, c.g. TIFS	.25 g
21	ϕ_m	- bank attitude, model	10 deg
22	ϕ	- bank attitude, TIFS	10 deg
23	p_m	- roll rate, model	5. deg/sec
24	p	- roll rate, TIFS	5. deg/sec
25	r_m	- yaw rate, model	2. deg/sec

Appendix VI (CONT'D)

RECORDING LIST

Digital Channel No.		Variable (all incremental values referenced to engage value)	Recording Scale Factor, units/volt
26	r	- yaw rate, TIFS	2. deg/sec
27	β_{IMTCG}	- sideslip, inertial, model transformed to TIFS c.g.	2. deg
28	β_I	- sideslip, inertial, TIFS	2. deg
29	$N_{y_{pm}}$	- lateral acceleration, pilot model	.1 g
30	N_{y_p}	- lateral acceleration, pilot TIFS	.1 g
31	α_g	- angle of attack, turbulence component, model	2. deg
32	*		
33	α_{TM}	- angle of attack, total, model c.g.	2. deg
34	β_{TM}	- sideslip, total, model c.g.	2. deg
35	V_{IM}	- velocity, inertial, model	66.7 ft/sec
36	$\Delta N_{z_{MCG}}$	- incremental normal acceleration, model c.g.	.25 g
37	$N_{y_{MCG}}$	- lateral acceleration, model c.g.	.1 g
38	*		
39	*		
40	*		
41	δ_{EC}	- elevator column deflection	1. in
42	δ_{AW}	- aileron wheel deflection	10. deg
43	δ_{RP}	- rudder pedal deflection	.5 in
44	δ_{e_m}	- elevator surface deflection, model	2.5 deg

NOTE: *Various signals recorded to check TIFS sensor system, check flight folders for particular signal recorded.

Appendix VI (CONT'D)

RECORDING LIST

Digital Channel No.	Variable (all incremental values referenced to engage value)		Recording Scale Factor, units/volt
45	δ_{a_m}	- aileron surface deflection, model	10. deg
46	δ_{r_m}	- rudder surface deflection, model	5. deg
47	T	- thrust, model engines	20,000 lb.
48	h_p	- pressure altitude, TIFS	2500 ft
49	h_{wh}	- wheel height, model	100 ft.
50	$G.S.D.$	- glide slope deviation (+ a/c high)	.05 deg
51	$Loc.Dev.$	- localizer deviation (+ a/c left of centerline)	.25 deg
52	$T.D.$	- touchdown pulse	---
53	$\delta_{e_{TIFS}}$	- elevator surface deflection, TIFS	2.5 deg
54	$\delta_{a_{TIFS}}$	- aileron surface deflection, TIFS	2. deg
55	$\delta_{r_{TIFS}}$	- rudder surface deflection, TIFS	10. deg
56	$\delta_{x_{Rt}}$	- throttle position, right, TIFS	10. deg
57	$\delta_{y_{Rt}}$	- side force surface deflection, right, TIFS	4. deg
58	$\delta_{z_{Rt}}$	- direct lift flap deflection, right, TIFS	4. deg